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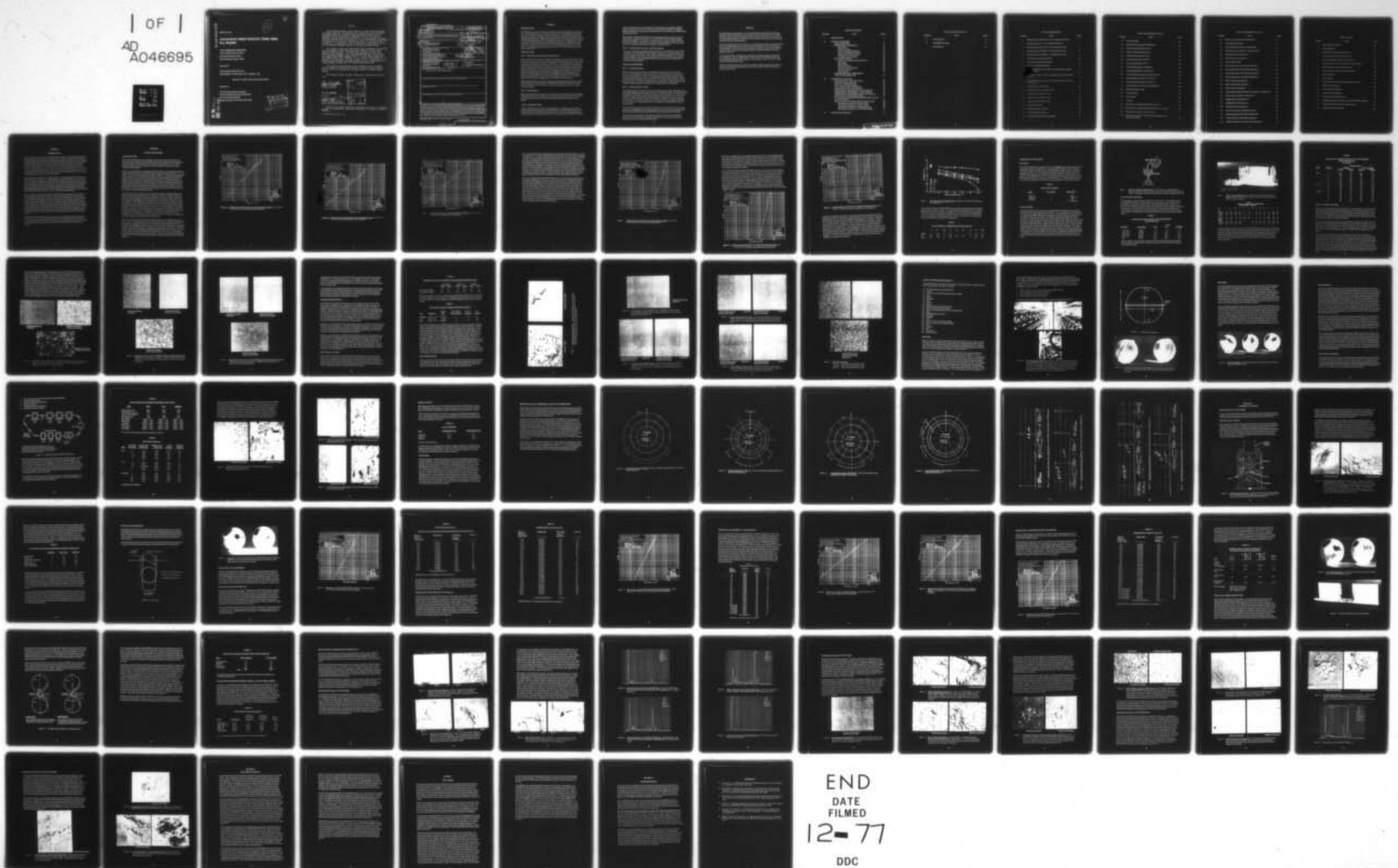

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EVALUATION OF POWDER PROCESSED TURBINE ENGINE BALL BEARINGS

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Aircraft Group
Government Products Division
West Palm Beach, Florida 33402

June 30 1977

Technical Report AFAPL-TR-77-26
Interim Report for Period May 1975 - December 1976

Approved for public release; distribution unlimited

Prepared for

Air Force Aero-Propulsion Laboratory
Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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This technical report was submitted by United Technologies Corporation, Pratt and Whitney Aircraft Group, Government Products Division under Contract F33615-75-C-2009. The effort was sponsored by the Air Force Aero-Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson AFB, Ohio under Project 3048, Task 304806 and Work Unit 30480665. Mr. R. D. Dayton administered the project for the Air Force. Mr. John R. Miner, Mr. P. F. Brown and Mr. J. R. Potts were the components technology manager, principal investigator and program manager, respectively, for Pratt and Whitney Aircraft.

This report has been reviewed by the Information Office (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Ronald D. Dayton

RONALD D. DAYTON
Project Engineer

FOR THE COMMANDER

Howard F. Jones

HOWARD F. JONES
Chief, Lubrication Branch
Fuels & Lubrication Division

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Work under this contract has demonstrated that powder processed bearing steels can be prepared to cleanliness standards consistent with the quality attainable in conventionally vacuum melted bearing steels, and that these alloys can be heat treated and processed into balls of aircraft quality. Rolling contact fatigue testing of three powder processed alloys in laboratory test devices has been completed and results revealed that an experimental alloy, EX00007, essentially a stainless steel composition, exhibited a fatigue life that was 2.2 times greater than that obtained in tests of powder processed M-50 alloy and 1.8 times the life observed for similar tests of VIM-VAR M-50 steel. On the basis of this performance, a recommendation has been made that a sufficient quantity of powder processed EX00007 alloy be procured for fabrication into aircraft gas turbine mainshaft bearings for subsequent endurance testing.

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SUMMARY

PROGRAM SCOPE

Pratt & Whitney Aircraft has conducted a program to fabricate and fatigue life test ball specimens of three different powder metal alloys. Using the best performing alloy from this program, twenty full-scale 140mm bore powder metal angular contact ball thrust bearings will subsequently be fabricated. Rolling contact fatigue life tests will then be conducted on these bearings in rigs particularly suitable for this type of program. This overall approach is believed to be a sensible and systematic way of investigating the feasibility of applying powder metal technology to bearing component manufacture and the subsequent demonstration of that capability in rig testing of a real usable product, the mainshaft thrust bearing of an existing engine. The following paragraphs summarize the results of the program conducted during this reporting period.

PROGRAM TASKS

Task I – Material Selection and Powder Metal Production

Three bearing alloys were selected by P&WA for preparation as powder metal products. AISI M-50 steel was one of the alloys chosen because of its widespread current use in service engines and, as such, would provide a baseline for the program. In the bench type tests conducted at P&WA prior to this program, this alloy had proven to be the best and most consistent performer of all the bearing materials evaluated. It is the baseline material for cast and wrought products and therefore, the powder product M-50 will be used to establish the baseline for the other two powder processed materials to be evaluated in this program. Those materials, also selected on the basis of their performance in P&WA rolling contact fatigue tests, are AISI T-15, a cobalt-tungsten type tool steel, and EX00007, an experimental high chrome stainless steel alloy made by the Carpenter Technology Steel Company. The selection was made with the concurrence and approval of the AFAPL/SFL Project Engineer.

P&WA worked directly with Carpenter Technology Steel Division to obtain powder prepared hot rolled ball wire of the three alloys. Non-metallic contamination and material porosity levels equal to those observed in the best quality conventionally processed vacuum melted steels were obtained.

Task II – Ball Fabrication

Marlin-Rockwell Division of TRW processed the ball wire into aircraft quality balls for P&WA rolling contact fatigue testing. Ball size was 15/16 inch diameter which is the same ball size used in both the bench type tests and in the mainshaft bearings to be evaluated in this program.

Task III – Ball Fatigue Testing

It has been P&WA's experience that it is considerably more demanding to make balls that perform with consistent and adequate fatigue life than it is to make rolling elements in a rod shaped roller or cone configuration. Also, engine service experience has demonstrated that balls are generally the shorter lived elements. For these reasons it was decided to evaluate the

powder processed alloys in the ball form in the screening stage of this program. P&WA's single ball test device was used in this effort as it has provided meaningful test results for P&WA through the years and many of the findings have been incorporated into P&WA engine bearing specifications.

Three groups of powder processed balls were tested in this program, each group made of a different alloy. Of these alloys; M-50, T-15, and EX00007, the best performer in single ball tests was EX00007. For purposes of comparison, data from the testing of VIM-VAR M-50 balls is included in this report. The powder processed EX00007 balls also performed better than the baseline VIM-VAR M-50 material in single ball testing.

Task IV – Selection and Procurement of Follow-On Material

This report, containing considerable fatigue performance and metallurgical evaluation data, is submitted to the AFAPL/SFL Project Engineer to assist him in the specification of the alloy to be used in the fabrication of the program mainshaft size bearings. It is recommended that EX00007 be that alloy. With the approval of the AFAPL/SFL Project Engineer, sufficient powder processed EX00007 bearing steel will be procured for subsequent fabrication of mainshaft bearings.

WORK TO BE PERFORMED

Task V – Bearing Procurement

P&WA will procure twenty 140mm bore mainshaft bearings fabricated from the alloy selected. The bearings will be made to the TF33 No. 4 design geometry as this design has a proven history of reliability. These TF33 engines power many military transports while running at bearing operating speeds of 1.44 million DN in normal engine operation. P&WA has tested this bearing design in rigs at speeds up to 3.0 million DN demonstrating the soundness of the design. The vendor who supplied this bearing design as a regular production item to P&WA will also fabricate the bearings for this powder metal processed program.

Task VI – Bearing Endurance Testing

The bearing endurance tests will be conducted by MAIC Division of Tribon Bearing Company using a P&WA designed 5-headed gearbox and up to 5 P&WA bearing rigs. The program will test 10 bearings simultaneously to minimize test operation time and program costs. The program will follow a sudden death approach which will provide four estimates of B-12.9 life which can then be reliably related to a B-10 life value with the confidence of a sample population of 20 bearings. The test loads, speeds and oil temperature will be comparable to those used in previous TF33 No. 4 bearing tests which were conducted by MAIC for P&WA using the same equipment.

All of the failed bearings will be subjected to analysis for the express purpose of identifying failure mode. Metallographic means will be utilized in this study and it is the intention that the same personnel who examined the failed ball specimens will examine the bearings.

A final report will be prepared. This report will include the information of this Interim Report and the results of Tasks IV through VI regarding the raw material procurement, bearing fabrication, and bearing endurance testing.

PREFACE

This Interim Report describes the work conducted during the period May 1975 through December 1976 by Pratt & Whitney Aircraft under Air Force Contract F33615-75-C-2009. This report presents results obtained under Task I through Task III of the Contract effort of test and analysis to determine the effects of powder metal processing upon the rolling fatigue resistance of selected ball bearing alloys.

This effort is being sponsored by the Air Force Aero Propulsion Laboratory, Air Force System Command, Wright Patterson Air Force Base, Ohio with Ronald D. Dayton, AFAPL/SFL as Project Engineer. John R. Miner, Paul F. Brown and J. Robert Potts, all of Pratt & Whitney Aircraft, served as Components Technology Manager, Principal Investigator and Program Manager, respectively.

The authors gratefully acknowledge the technical and coordination assistance contributed by the following: Thoni V. Philip, Gregory J. Del Corso and C. Donald Steinwedel of Carpenter Technology Corporation; and Arthur S. Irwin, Ronald F. Spitzer and Verle D. Kifer of Marlin Rockwell Division, TRW.

This report submitted on June 30, 1977 is in compliance with the requirements of sequence A004 of the Contract Data Requirements List, and was prepared under the Contractor's reference FR No. 8481.

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SECTION I

INTRODUCTION

Service experience of existing aircraft turbine engines indicates a continuing need for bearing materials which have greater resistance to rolling contact fatigue. Advanced engine designs require bearing materials capable of providing superior fatigue resistance at progressively higher operating speeds, loads and temperatures. In the broad sense, it is essential to the continued evolution of aircraft gas turbine engines to find ways of improving presently used highly developed bearing alloys and to develop means for effectively processing advanced alloys which have proven difficult to work but have distinct potential for operation at elevated temperatures. Powder metal technology provides an extremely promising approach to these technical requirements, and has the further merit of potential cost savings when the related manufacturing techniques are fully developed and applied.

A principal source of rolling contact fatigue failures in present high quality M-50 bearings for aircraft engines is the occurrence of undesirably large carbide formations in the metal matrix. These act as points of weakness under the highly cyclic loading experienced in bearing operation, and ultimately become the origin of fine cracks which lead to spalling and bearing failure. Although extended efforts have been made by metal producers, bearing manufacturers and engine developers to devise ways of minimizing carbide size, insuring uniform carbide distribution and achieving superior quality control in bearings, all conventional processing techniques have failed to provide the necessary control of carbide size and distribution.

The use of powder metal is a promising way to produce alloys with highly refined carbides since the carbide size is limited by the size of the powder particles and does not change as a result of subsequent processing. Likewise, a highly uniform distribution of carbides should be obtained in the final product because of the random mixing of particles which occurs in powder preparation and handling. To date, evaluation of powder metal processed materials indicates that superior physical properties are achievable and that the material is more resistant to forming stresses. There also are indications that materials which are extremely difficult to form after conventional processing exhibit much better formability when produced from powder metal. Powder metal technology therefore offers both a way of upgrading currently used bearing steels and a way of using advanced materials which have proven intractable in the past.

Although the potential of powder metal for rolling contact bearings has been recognized for several years, it has been only within the relatively recent past that the necessary purity of the powdered alloy could be assured. Experience has demonstrated that details of the powder producing and processing procedures can be critical to the achievement of a satisfactory product.

SECTION II

TECHNICAL DISCUSSION

ALLOY SELECTION

The review of P&WA single ball tester rolling contact fatigue data disclosed that of the many materials examined over the past fifteen years only two alloys have exhibited fatigue lives that equalled or surpassed M-50 steel performance. These alloys are T-15, a high tungsten-cobalt tool steel and a stainless steel alloy, EX00007, developed by Carpenter Technology Steel Company.

There is a certain difficulty in assessing the relative performance of materials when the data being compared has been acquired at different points in time spanning a period of years. This would be true of any materials evaluation program regardless of the property being evaluated and is certainly the case for rolling contact fatigue resistance as evaluated in the single ball fatigue rigs. Due to this time factor, the performance of the M-50 baseline material has changed over the years because of improvements in processing, manufacturing and quality control. Because of this fact the B-10 life data presented herein is generally identified with the calendar year of the test to minimize confusion. This data is presented in the form of Weibull life distribution plots with attendant supportive information contained in insets in these figures. Due to space limitations not every baseline set of data for M-50 accumulated over the years has been included in this report.

Also, during the course of the conduct of the single ball materials evaluation program not every test material was evaluated with every lubricant of interest. This again presents some difficulty in drawing conclusions regarding comparative performance. However, M-50 has been tested quite thoroughly in the two most widely used aircraft gas turbine engines oils; namely MIL-L-7808 and MIL-L-23699. Results of these tests, shown in Figures 1A and 1B, reveal that there is no statistically significant difference in the B-10 lives for these two lubricants as tested in the single ball rigs, circa 1965. The ratio of the B-10 life corresponding to the MIL-L-23699 oil vs. that for the MIL-L-7808 oil is 1.18. Applying the Ref. 1 technique for analyzing confidence levels to these sets of data produced a 53% confidence rating that this observed difference is real. This difference is considered insignificant and therefore had no influence on the performance comparison study that led to the choice of T-15 and EX00007 alloys as materials worthy of being used to evaluate the feasibility of applying powder metal technology to bearing component manufacture.

The T-15 alloy was tested in 1965 and the observed B-10 life of 15.57 million stress cycles (Figure 2) was 1.77 times greater than the longest lived M-50 steel tested up to that time. This life difference, although indicating a gain, is not considered statistically significant because the single ball test program population normally consists of twenty tests and the corresponding confidence bands for twenty tests are fairly broad. Application of the Reference 1 statistical criteria to such data has established that fatigue life levels would have to differ by three times or more to have at least 90% confidence that the difference is real. The 1.77 improvement factor meant that the confidence level was only 69%. At the time this data was obtained this confidence level was not considered high enough to warrant further evaluation of the material until now.

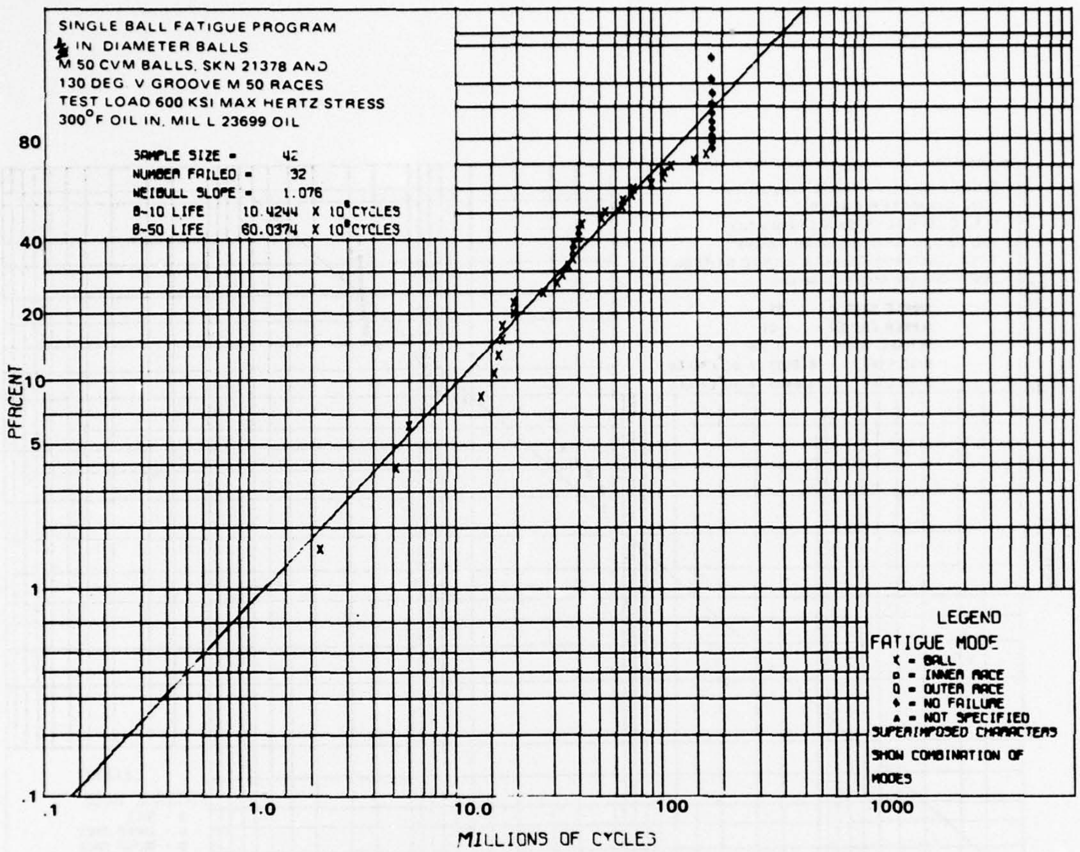


Figure 1A — *Weibull Analysis of Baseline M-50, 1965, Single Ball Test Data. B-10 of 10.42 x 10^6 stress cycles was obtained for this population.*

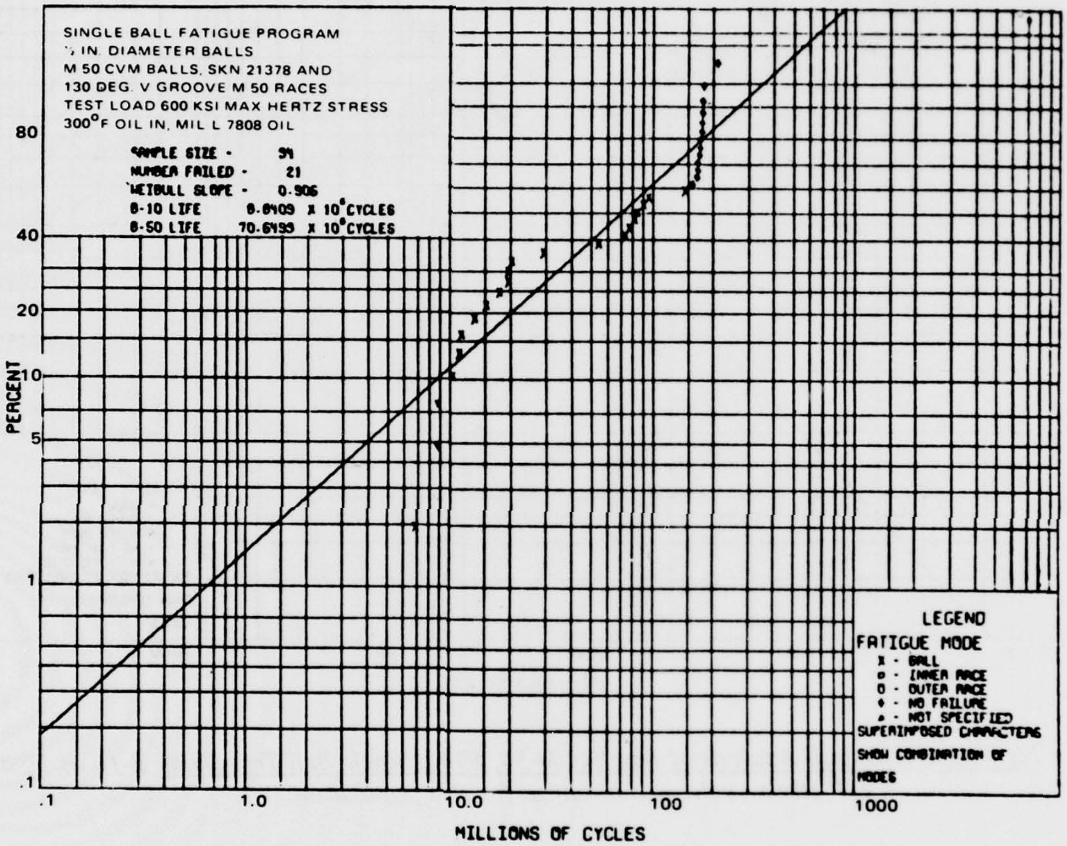


Figure 1B Weibull Analysis of Baseline M-50, 1965, Single Ball Test Data. *B-10 of 8.84 x 10^6 stress cycles was obtained for this population.*

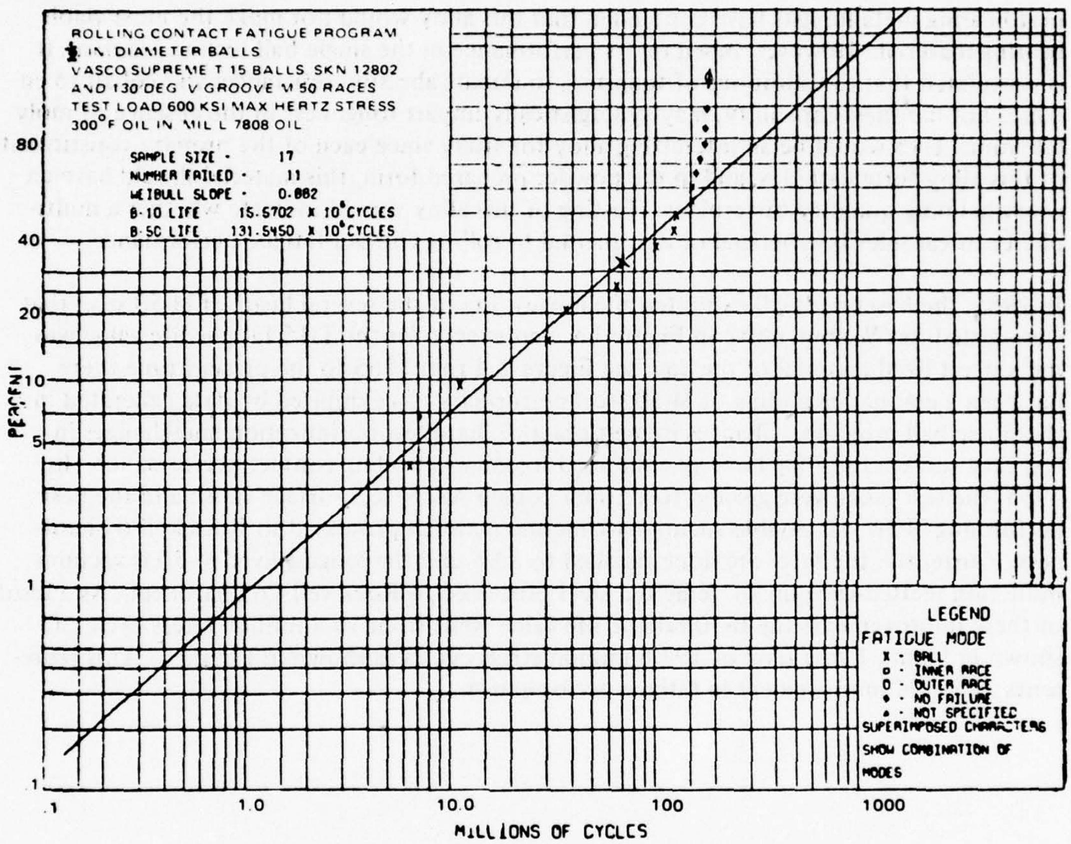


Figure 2 *Weibull Analysis of T-15, 1965, Single Ball Test Data. B-10 of 15.57 x 10^6 stress cycles was obtained for this population.*

T-15 is a highly alloyed steel containing tungsten, cobalt, vanadium and chromium. A notable omission in T-15 is that of molybdenum, normally added to steels to impart "toughness" a property that is not readily defined by scientific means but is one that relates to the ability of an alloy to absorb impact shock without fracturing. Since T-15 lacks molybdenum, expert bearing metallurgists have contended that this alloy would not make the most viable bearing material. However, based on its performance in the single ball testing program, it is postulated that the additions of tungsten, to impart abrasion resistance, and cobalt to enhance hot hardness capability, may synergistically impart toughness in the absence of molybdenum. T-15 would be an interesting alloy for study since each of the primary constituents of this alloy form carbides, and in the powder prepared form, this material should have an overwhelming quantity of carbides. Testing of this alloy should indicate whether a multiplicity of carbides is beneficial or detrimental to rolling contact fatigue performance.

In 1965, the baseline M-50 exhibited the longest life of the several heats of M-50 steel that were tested, see Weibull curve in Figure 1A, and except for the T-15 fatigue life value was the longest lived material of the day, see Figure 2. From 1965 to the present time there has been a gradual upgrading of M-50 steel performance as exhibited by data generated in the single ball program. Changes in melt-practice, hardness optimization and changes in test race surface finishing have all combined to enhance rolling contact performance. In 1965, the test races were ground to a 10 microinch AA or less surface finish and the best performing M-50 was double vacuum-arc melted material processed to Rockwell 64 hardness. Currently, the races are hone finished to 5AA and the longest lived M-50 is vacuum induction melted-vacuum arc remelted steel processed to Rockwell C62 hardness. As a result of these improvements the B-10 fatigue life value went from 10.4 million stress cycles as shown in Figure 1 to a level of 197.8 million stress cycles as shown in Figure 3. This represents a 19 fold improvement in fatigue performance.

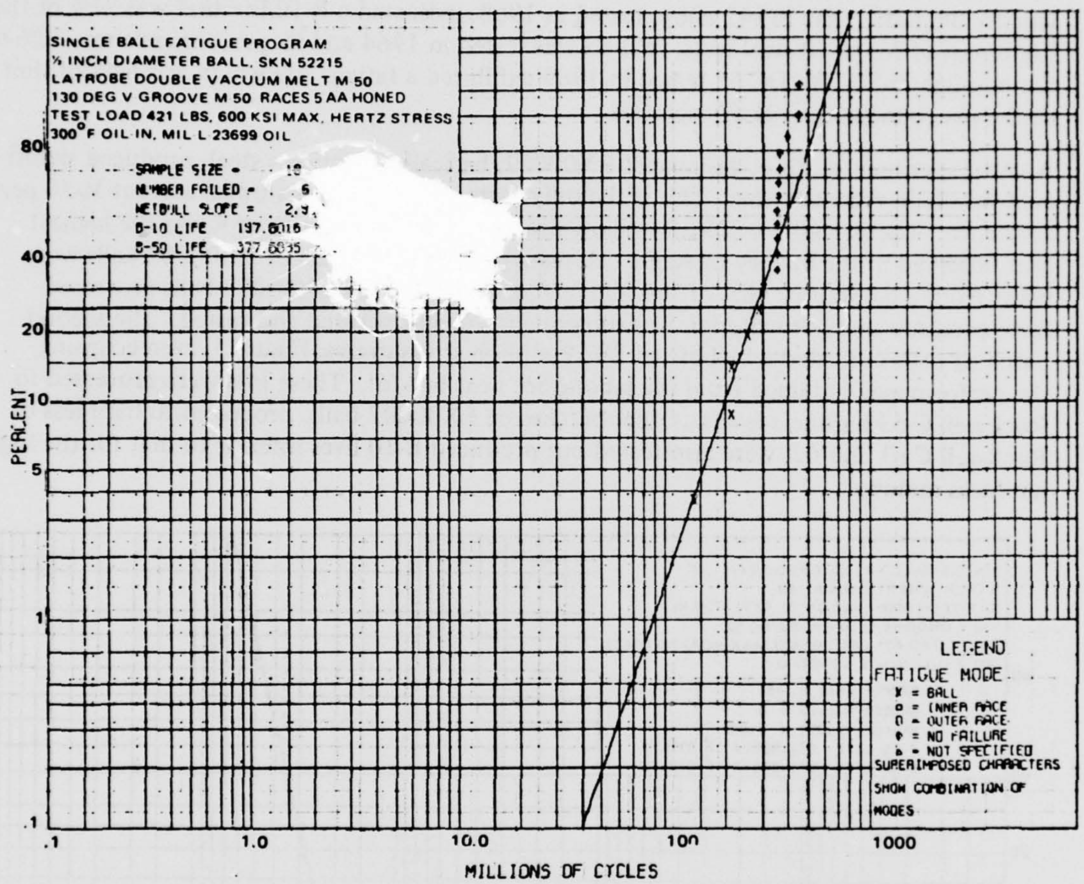


Figure 3 *Weibull Analysis of Best M-50, 1970, Single Ball Test Data; B-10 of 197.80 x 10^6 stress cycles was obtained for this population.*

Many other candidate alloys were evaluated since 1965 and none of these exhibited fatigue life values that equaled M-50 performance. Notable among the many were WB-49, BG-42 and WADC-65, alloys which were mentioned in the Air Force request for proposal as being worthy of study. The BG-42 alloy, tested in 1968, indicated a B-10 life that was 71% of the life observed for M-50 steel tests. WB-49 was tested in 1964 and its performance was 32% of the baseline M-50. WADC-65 tested in 1969 exhibited a fatigue life which was 64% of that of the program baseline M-50 material.

A new experimental alloy, designated EX00007, basically a stainless steel, produced significant results in recent testing. This is the only material to equal or surpass current M-50 performance. The B-10 life of 231.8 million stress cycles shown in Figure 4 was the highest ever observed in the history of single ball testing. This first batch of EX00007 balls was made from a laboratory heat of this alloy. A second batch of EX00007 balls processed from production ingot material, was subsequently manufactured and tested. The second batch of balls indicated a ball life of 282.9 million stress cycles, Figure 5, even eclipsing the performance obtained from the laboratory heat ball lot. These lots were processed to Rockwell C-63 hardness levels. Other batches of EX00007 balls, processed to hardness of Rockwell C 61 and 62, were also tested but produced B-10 lives inferior to that for the higher hardness material.

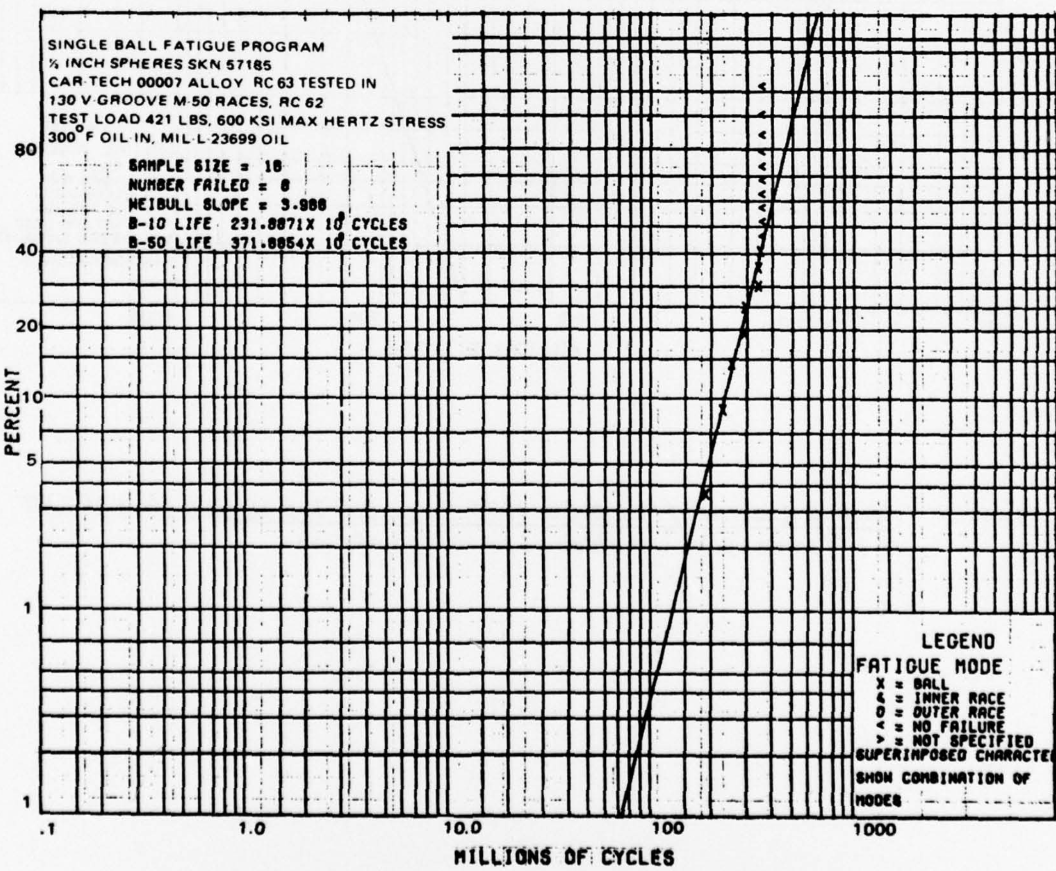


Figure 4 Weibull Analysis of EX00007, 1974 Single Ball Fatigue Test Data. B-10 of 231.9 x 10⁰ stress cycles was obtained for this population.

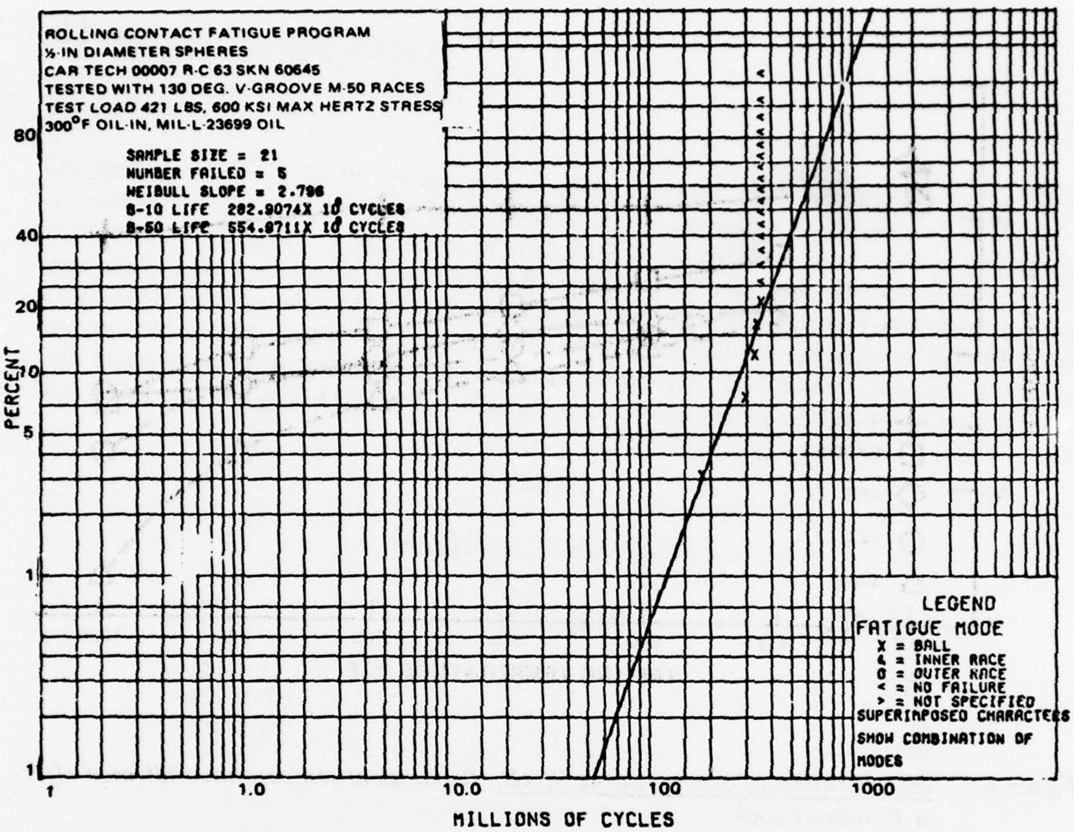


Figure 5 *Weibull Analysis of EX00007, 1975, Single Ball Fatigue Test Data. B-10 of 282.91 x 10^6 stress cycles was obtained for this population.*

In addition to fatigue life performance, this program focused on those alloys which also exhibited improved hot hardness and corrosion resistance beyond the levels available from AISI M-50 steel, the current aircraft mainshaft ball bearing material standard. Available data on the hot hardness retention of AISI T-15 and EX00007, as presented in Figure 6 shows that these alloys are superior not only to M-50 but to other conventional stainless bearing alloys such as 14-4 and 440-C. Available information on corrosion resistance does not exist on a common basis. Thus it is difficult to effect an absolute judgment in this regard since it is the opinion of many metallurgists that an alloy's chromium content governs the material's corrosion resistance. The alloy, EX00007, which has 14% chromium, would have superior corrosion resistance compared to M-50 and T-15 which both contain only 4% chromium. T-15 because of its superior hot hardness characteristic is ranked second to EX00007 and slightly above M-50 steel.

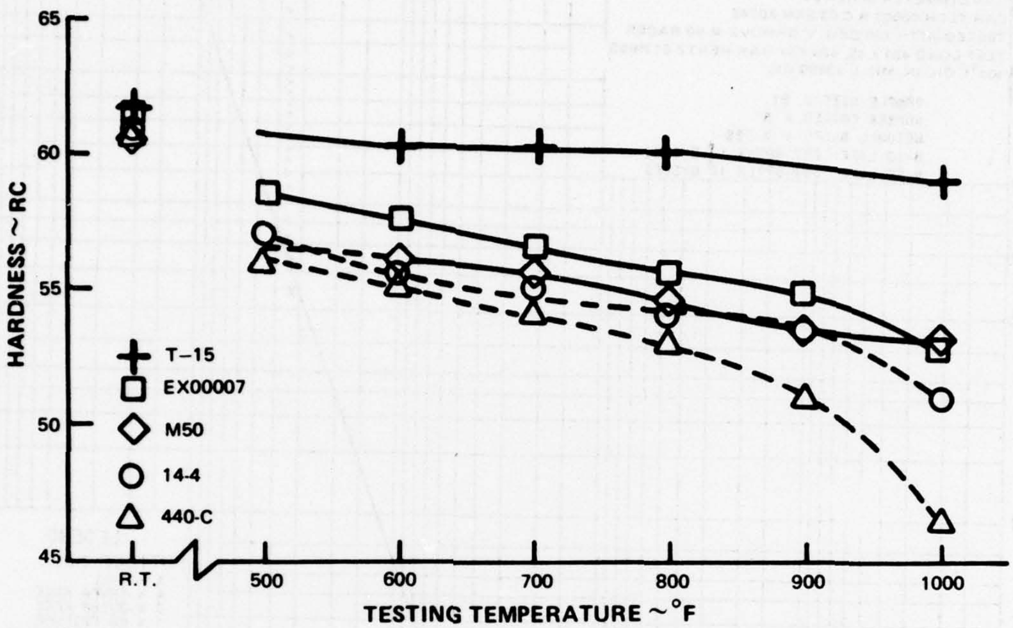


Figure 6 *<u>Hot Hardness of Some Bearing Steels.</u> Readings at temperature indicated after a 30 minute soak*

The three alloys, M-50, T-15 and EX00007, have chemical compositions which are significantly different as noted in Table 1. As a result they produce microstructures with marked differences in not only the numbers of carbides but in their distribution and morphology as well. It remains to be determined if the different structures will produce significant differences in rolling contact fatigue performance. That is, is it carbide size or quantity that has the most influence on rolling contact fatigue life?

TABLE 1

ALLOY CHEMICAL COMPOSITION (WEIGHT PERCENT)

	C	Cr	Mo	V	W	Co	Cb	Si	Mn
00007	1.1	14.0	2.0	1.0	– –	– –	0.3	0.3	0.4
T-15	1.6	4.0	– –	5.0	12.0	5.0	– –	0.3	0.3
M-50	0.8	4.0	4.2	1.0	– –	– –	– –	0.2	0.2

POWDER METAL PROCESSING

Ingot History

The starting materials for this program were conventionally processed ingots prepared either by vacuum induction melting (VIM) or vacuum induction melting-vacuum arc remelting (VIM-VAR) techniques. Single heats of both AISI M-50 and AISI T-15 were available and were used to produce the necessary powder for these two materials. However, since the EX00007 alloy is generally not available in production quantities, it was necessary to combine two smaller laboratory heats in order to produce the desired quantity of powder. The melt histories of the respective heats are presented in Table 2. Chemical analysis confirmed that each heat conformed to the specified chemical composition of the respective alloys.

TABLE 2

INGOT MELT HISTORY

Alloy	No. of Heats	Melt Process
AISI T-15	1	VIM
AISI M-50	1	VIM-VAR
EX00007	2	1 – VIM 1 – VIM-VAR

Powder Processing

Conversion of the ingots into powder was accomplished with equipment which is schematically represented in the sketch shown in Figure 7. The atomizing system is enclosed and is evacuated to a pressure level which removes all traces of atmospheric contamination prior to remelting of the ingot. Melting is accomplished by induction heating techniques in a crucible in the upper section of the unit. After the metal becomes molten it is poured through an atomizing nozzle into another vacuum chamber located below the remelt chamber. The molten metal is discharged as refined droplets from the nozzle. High velocity inert gas bled into the chamber cools the droplets as they emerge from the nozzle. Vacuum pumping acts continuously to maintain the chamber pressure well below atmospheric. The cooled droplets solidify and drop to the bottom of the lower chamber. This powder now contains carbides that are many times smaller than those that were present in the original large ingot. The powders are to be reconsolidated into new ingots at temperatures well below alloy melt temperatures in order to ensure that no coalescence or growth of the alloy carbides will occur. By means of this process it is assured that the final product will exhibit refined carbides.

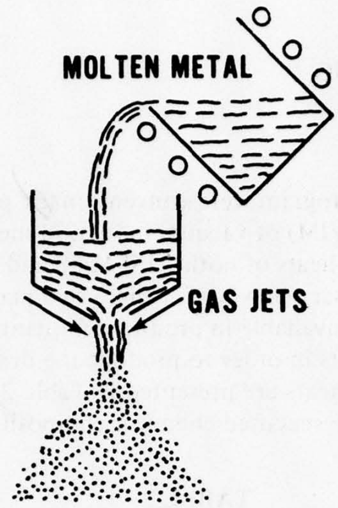


Figure 7 *Process for Making Prealloyed Powder. Under vacuum, a prealloyed ingot is melted in the upper crucible and the melted metal is poured through an atomizing nozzle. Cooling gas jets solidify the metal droplets, forming the prealloyed powder.*

Powder Screening and Blending

For this program, powders smaller than 0.007 inch were retained. Powder separation was accomplished by sieving the powders in glove boxes under an inert gas to prevent oxygen and nitrogen contamination of the powders. After this rough sieving the powders were still kept in an inert gas environment and then were blended to provide homogenous mixtures. A sample of the T-15 alloy powders is shown in Figure 8. Samples of the blends of the three powders were subsequently screened and the particle size distribution listed in Table 3 was obtained. The table indicates that the bulk of the powders were smaller than 0.0034 inches.

TABLE 3

BLENDED POWDERS PARTICLE SIZE DISTRIBUTION WEIGHT PERCENT

Mesh Size	Average Size	Alloys M-50	T-15	EX00007
– 80, +100	0.0064"	1.0	1.0	3.0
–100, +140	0.0050	9.1	10.2	15.2
–140, +200	0.0034	16.8	17.6	21.1
–200, +325	0.0023	32.7	30.5	28.3
–325	0.0017	40.4	40.7	32.3

Chemical analysis of replicate samples taken of the three powder blends produced results shown in Table 4, which indicated no significant deviation from the specified composition of the individual alloys.

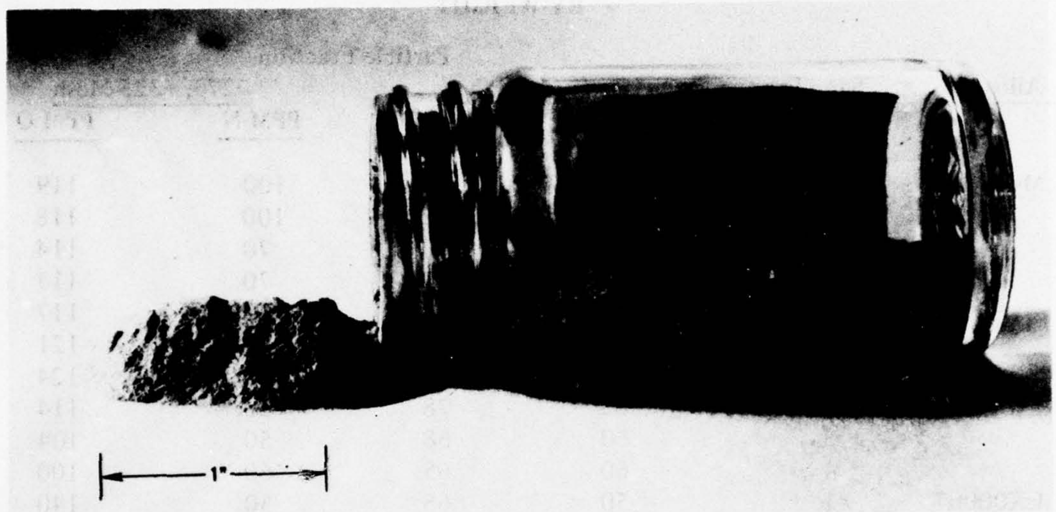


Figure 8 *AISI T-15 Alloy Blended Powder.* *Particle sizes in this blend range from a maximum 0.006" diameter to less than 0.002" diameter. Particle size distribution is presented in Table 3.*

TABLE 4
CHEMICAL COMPOSITION OF BLENDED POWDERS
WEIGHT PERCENT – ELEMENTS

Alloy	C	Cr	Mo	V	W	Co	Cb	Si	Mn	Ni	P	S	Cu
M-50													
Sample 1	.83	4.42	4.36	1.01	<.1	.01	--	.29	.25	.10	.01	.002	.04
Sample 2	.82	4.22	4.36	1.02	<.1	.01	--	.29	.25	.10	.01	.002	.04
Sample 3	.82	4.23	4.34	1.01	<.1	.01	--	.28	.24	.10	.01	.002	.04
T-15													
Sample 1	1.52	4.70	.02	4.87	12.68	5.07	--	.25	.26	.08	<005	.004	.01
Sample 2	1.52	4.80	.02	5.25	12.43	5.11	--	.25	.28	.07	<005	.004	.01
EX00007													
Sample 1	1.10	13.91	2.00	1.05	--	--	.27	.30	.42	.06	.011	.005	.01
Sample 2	1.10	14.01	2.02	1.03	--	--	.32	.31	.43	.08	.016	.003	.02
Sample 3	1.09	14.11	2.03	1.04	--	--	.32	.31	.44	.07	.016	.003	.02

Typically, nitrogen and oxygen content of vacuum melted alloys are low, usually in the range of 20 to 40 parts per million. Powder processing will naturally add somewhat to these levels. Analysis of the alloy powders prepared in this program for oxygen and nitrogen content revealed the values shown in Table 5 which demonstrated that the powder preparation process did not increase the oxygen and nitrogen levels to prohibitive values. The values in Table 5 are not considered excessive and are, in fact, indicative of excellent powder processing technology.

TABLE 5

OXYGEN AND NITROGEN CONTENT OF ALLOY POWDERS (PARTS PER MILLION) BY WEIGHT

Alloy	Sample	Particle Fraction −60 Mesh PPM N	−60 Mesh PPM O	−270, +325 Mesh PPM N	−270, +325 Mesh PPM O
M-50	1	100	83	100	119
	2	100	72	100	118
	3	70	60	70	114
	4	70	61	70	117
	5	50	82	60	117
	6	50	99	60	121
T-15	1	60	71	70	124
	2	60	78	60	114
	3	60	68	50	104
	4	60	65	60	100
EX00007	1	50	65	50	140
	2	50	76	50	135
	3	90	41	80	105
	4	90	57	80	105
	5	90	81	90	127
	6	80	94	80	129

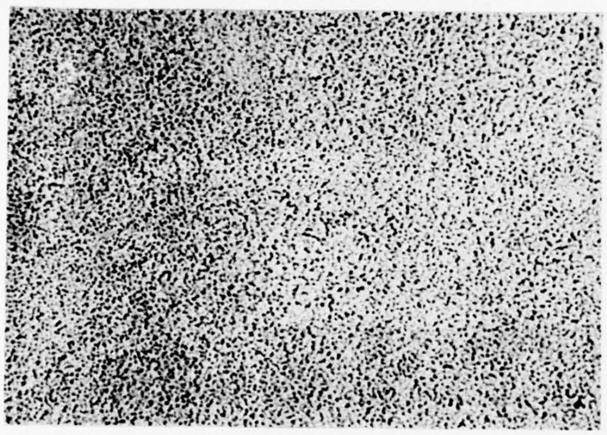
Powder Consolidation and Results

Hot isostatic pressing was the method employed for the consolidation of the powders. Hot isostatic pressing employs simultaneous application of elevated temperature and isostatic pressure delivered by an inert gas to effect consolidation of powders contained in a metal can. At elevated temperatures, the can softens and the pressure developed by the gas external to the can causes it to collapse against the powders, thereby compressing the heated powders into an ingot of near theoretical density.

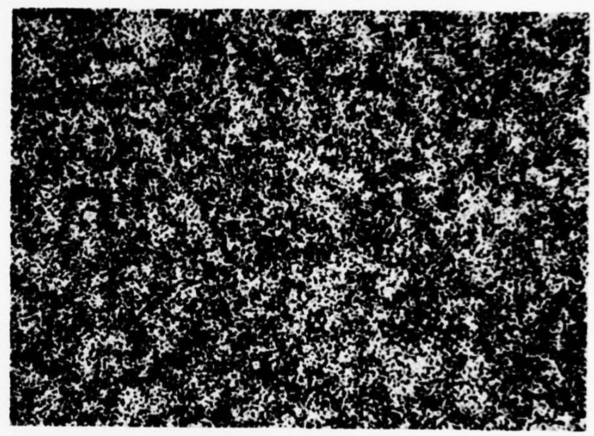
In this program the blended powders were poured into the stainless cans under vacuum to preclude oxygen contamination. After filling, the cans were sealed by welding a lid on to the open end. The cans, approximately 52 inches tall and 7 inches in diameter, were placed into the hot isostatic pressing furnace. Powder consolidation was accomplished by heating the containers to 2150°F, under a gas pressure of 15,000 pounds per square inch, for 4 hours.

The selection of 2150°F for powder consolidation was the result of a compromise to process the three alloys at the same time to minimize expense. Thus, the temperature had to be high enough to initiate and promote T-15 compaction without seriously overheating the M-50 alloy. A review of the results indicates that the 2150°F consolidation temperature did meet the criteria. AISI T-15 powder consolidation was well advanced while the AISI M-50 microstructure was not severely penalized. The effects were considered correctable since the alloys were to be thermally treated and forged several times in subsequent processing operations. These operations would work the material to homogenize the microstructure, thereby compensating for the non ideal temperature used during consolidation of the two alloys.

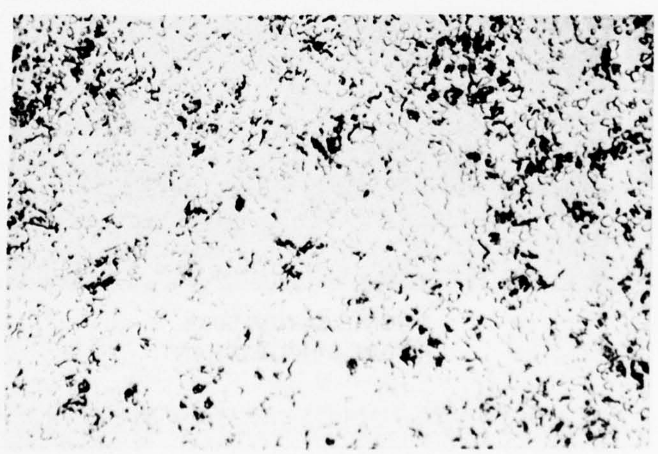
The effects of processing at 2150°F was apparent from a study of the three alloy microstructures. EX00007 exhibited an ideal microstructure which was homogenous, with the refined carbides uniformly dispersed. Figure 9 presents the EX00007 microstructure as it appeared after being hot isostatically pressed and annealed. Maximum carbide size is estimated to be 0.0001 inch. AISI T-15 revealed the microstructure as presented in Figure 10. Many more carbides are present, as expected, and again carbide size is less than 0.0001 inch. The darker regions in the photograph are regions of tungsten which did not diffuse uniformly during the hot isostatic pressing operation. This feature was not considered serious as subsequent thermal and mechanical processing would completely disperse the tungsten. AISI M-50 exhibited the fewest carbides of the three alloys, as can be seen in Figure 11. Again carbide dispersion was uniform and these carbides were smaller than 0.0001 inch. However, in some isolated regions it was observed that carbide precipitation in grain boundaries did occur to a minor degree, a result of overheating of the alloy. This condition would also be corrected by the subsequent hot forging, rolling, annealing and hardening operations.



MAGNIFICATION 100X
UNETCHED

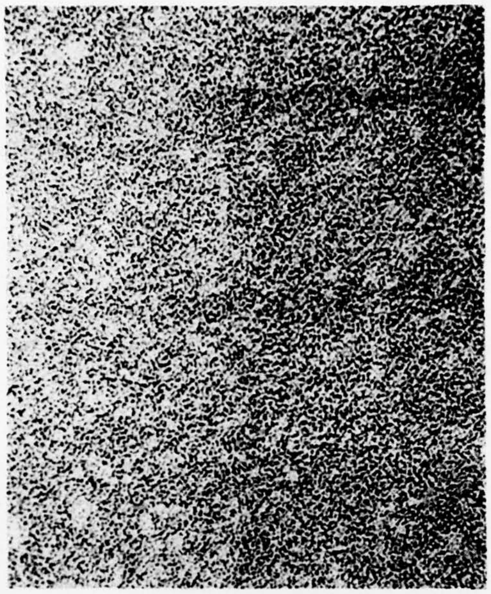


MAGNIFICATION 100X
PICRAL & HCL ETCHANT



MAGNIFICATION 500 X
PICRAL & HCL ETCHANT

Figure 9 *P/M EX00007 Alloy After 2150°F/15 KSI Hip Operation and Sub-Critical Anneal. Carbide size and distribution can be appreciated only at 500X magnification. Carbides appear white in the photomicrograph.*



MAGNIFICATION 100X
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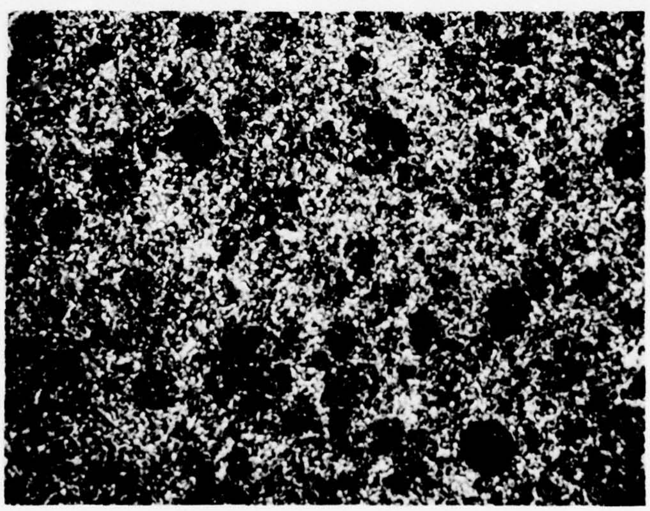
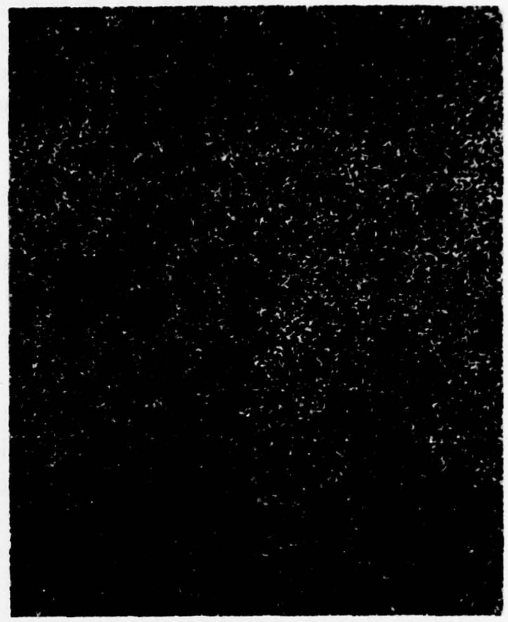


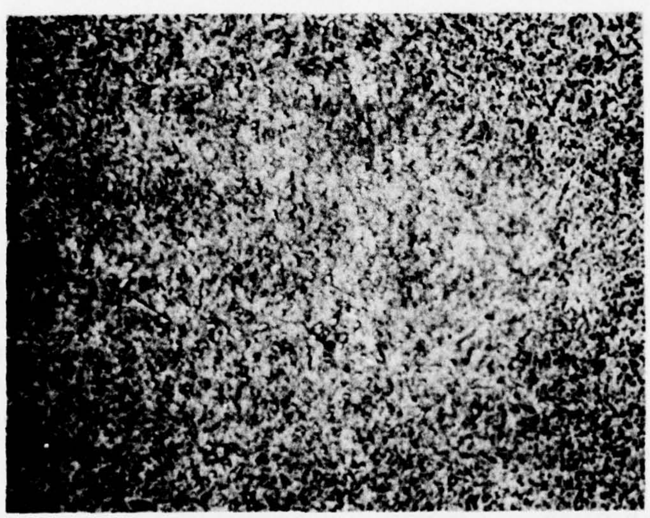
MAGNIFICATION 500X
PICRAL & HCL ETCHANT

Figure 10 *P/M AISI T-15 After 2150°F/15KSI Hip Operation and Sub-critical Anneal. Carbides are more numerous in this alloy. Carbide size and distribution are evident in the 500X illustration. The dark spots are thought to be tungsten-rich regions.*

MAGNIFICATION 100X
UNETCHED



MAGNIFICATION 100X
PICRAL & HCL ETCHANT



MAGNIFICATION 500X
PICRAL & HCL ETCHANT

Figure 11 <u>*P/M AISI M-50 Alloy After 2150° F/15KSI Hip Operation and Sub-critical Anneal.*</u> *Carbides are least numerous in this alloy. Carbide size and distribution are readily visible in the 500X illustration.*

Metallurgical examination of the three materials for cleanliness revealed that the inclusion content was low. A Jernkontoret rating of 1/2 was assigned to each alloy. This rating is typical of the quality achieved with the cleanest of vacuum melt alloys. The inclusions that were observed appeared to be globular oxides which is one of the typical contaminants found in bearing steels.

In recapitulation, the metallurgical examination revealed complete compaction of the ingots, uniform microstructures of the individual alloys, and material cleanliness that was equal to that exhibited by the cleanest alloys produced by conventional vacuum melt processing. Based upon the excellence of these results the decision was made to accept the materials for processing into barstock for subsequent ball forming.

Forging and Rolling Operations

The initial step in this process was the removal of the stainless steel cans from the three alloy ingots by machining. Upon completion of the machining operation, billet size was approximately 6.5 inch diameter and approximately 50 inches in length. To facilitate handling, the billets were cut in thirds. For hot forging, the sections were placed in holding furnaces. AISI M-50 sections were heated to 2000°F and the AISI T-15 and EX00007 alloy sections were heated to 2100°F. A hydraulic press was used to forge the billets. Billet size was changed from 6.5 inch diameter to 3.0 inch diameter in two passes through the press, with the material being returned to the holding furnace between the first and second pass. Sub-critical annealing operations were conducted to preclude cracking of the bars due to high residual stresses developed during the forging operation.

Samples were cut from the bar ends to assess product quality a second time. This examination confirmed product cleanliness. It was also observed that corrections of T-15 and M-50 microstructural deficiencies mentioned previously were partially accomplished. The metallurgists contended that these alloys would not show any deleterious effects from the 2150°F consolidation temperature after all processing was completed.

Processing continued with the machining of the billet surfaces to remove decarburized zones developed during the forging operations. Approximately 0.100 inch was removed from the billet diameters. An anti-oxidant coating was then applied to the billets to minimize decarburization during subsequent hot rolling operations. During hot rolling the billets were changed from 3 inch diameter stock into 0.8125 inch diameter bars, 26 feet long. The bars were cut in half to facilitate handling, were then fully annealed and subsequently centerless ground to 0.750 inch diameter to remove surface flaws and to provide the barstock diameter requested by the ball manufacturer.

Final Inspection of Barstock

Sections taken from each bar for chemical analysis to identify major constituents and the interstitials, i.e. nitrogen and oxygen, revealed no changes from those values reported previously. Alloy chemistry was unchanged from the results presented in Table 4. Results from the nitrogen and oxygen measurements obtained on two barstock sections of each alloy indicated no significant changes from that analysis obtained previously for the starting powders. Table 6 compares the results of the powder and barstock analyses.

TABLE 6

NITROGEN AND OXYGEN CONTENT P/M PROCESSED BEARING STEELS

	AISI M-50		AISI T-15		EX 0007	
	PPM N	PPM 0	PPM N	PPM 0	PPM N	PPM 0
Avg. Powder Results	75	97	74	96	63	91
Avg. Barstock Results	90	95	95	110	75	100

Metallographic study of inclusion content determined that all three alloys were exceptionally clean and a Jernkontoret (J-K) rating of 1/2 was assigned to the materials. Table 7 presents the results obtained on samples submitted to P&WA by Carpenter Technology, the material supplier.

TABLE 7

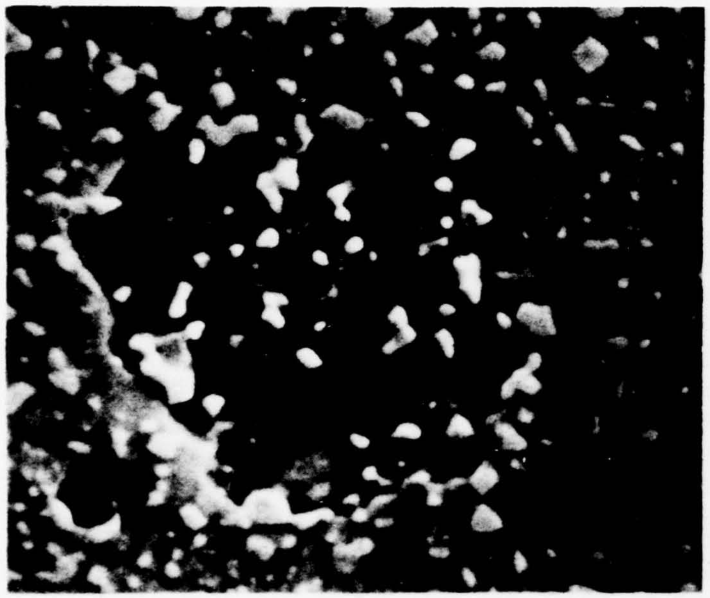
INCLUSION RATING OF THREE P/M BEARING STEELS

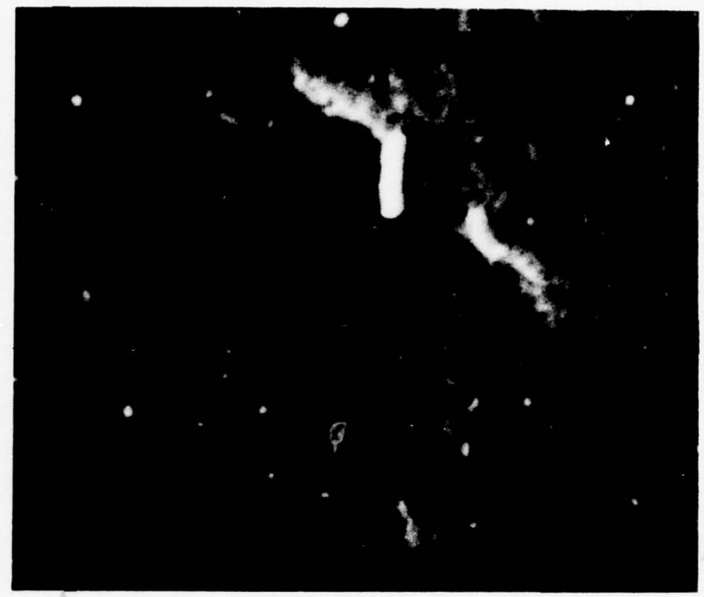
Alloy	Sample Size	Sample Area	No. of Fields With Inclusions	No. of Inclusions	J-K Rating
EX00007	0.625" x 1.25"	0.78 in^2	7	9	1/2
T15	0.75" x 1.5"	1.13 in^2	5	6	1/2
M-50	0.75" x 1.25"	0.94 in^2	4	4	1/2

The observed inclusions were identified as silica or alumina by electron microprobe analysis. Figure 12 presents scanning electron micrographs of the two types of inclusions. The largest inclusion dimension was 0.00075 inch. To put this cleanliness level in perspective, conventional vacuum melt material specifications allow a J-K rating of 1 for alumina/silicate inclusions with particle size width of 0.0005 inch and length up to 0.010 inch. Jernkontoret Standards specify that the materials be viewed at a magnification of 100X when the cleanliness value is assigned. Photomicrographs of the subject materials taken at 100X did not adequately magnify the inclusions to allow proper identification and sizing. Figure 13 is an example of alloy appearance at 100X. Therefore, additional photomicrographs were taken at 500X. Regions which were considered to contain inclusions of the largest size were photographed to demonstrate that even these areas met the J-K Standards for a rating of 1/2. Figures 14, 15 and 16 are illustrations of transverse and longitudinal sections of the three alloys. Figure 17 presents the microstructures of the three alloys as they appear in the annealed state. These photomicrographs were taken at 1000X to enlarge the carbides for closer examination. The carbides are estimated conservatively to be half the size of what is typically obtained when the alloys are conventionally processed.

BALL MANUFACTURE

This section of the report describes the operations involved in the conversion of the barstock into high quality balls. Ball diameters are to deviate less than ten millionths of an inch and the ball surface finish target is one microinch AA or less. This quality is the result of the many meticulous steps that are required in order to manufacture such a ball.

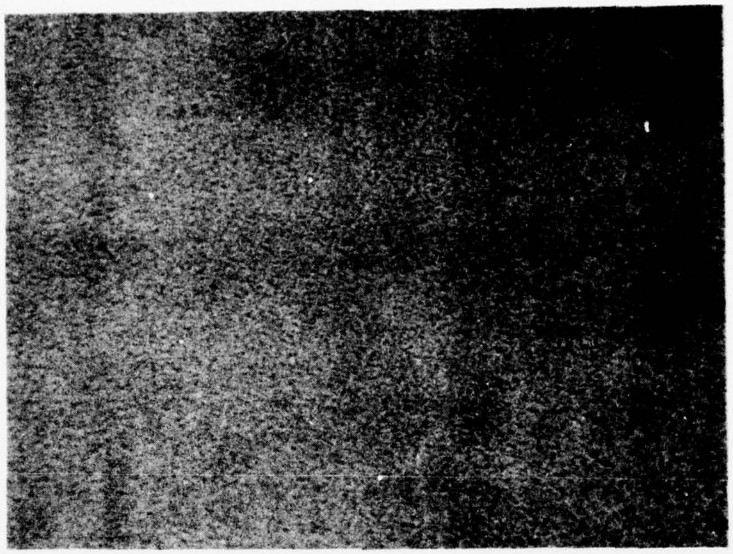




ETCHANT: NONE

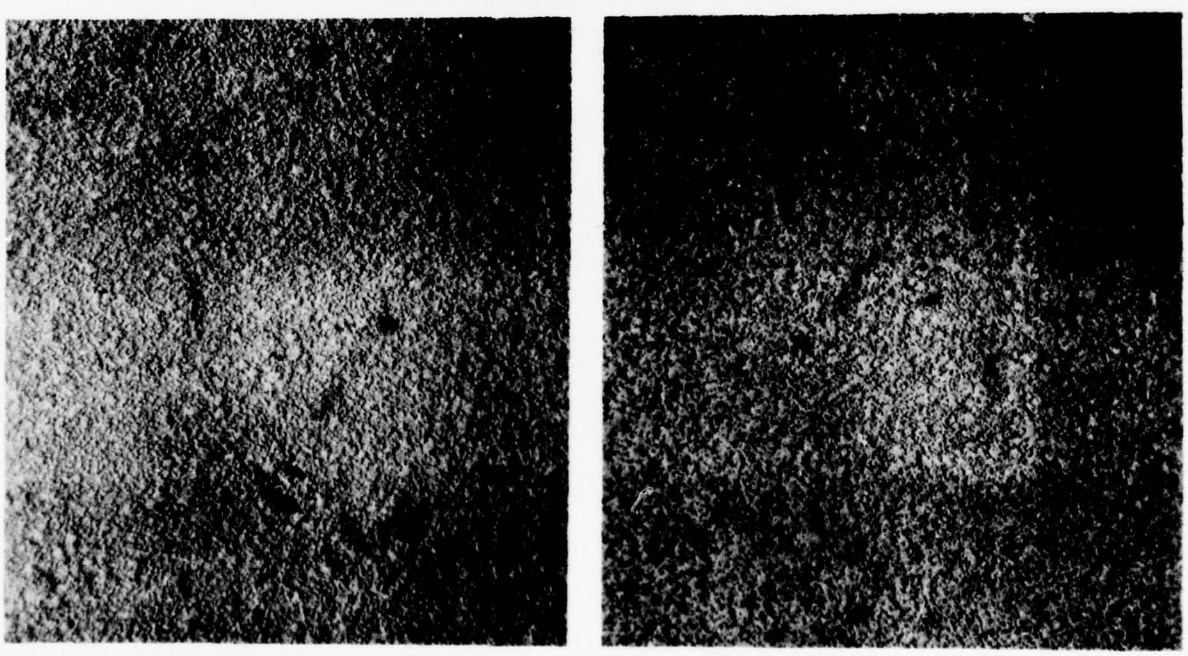
MAGNIFICATION 3000X

Figure 12 <u>*Scanning Electron Micrographs.*</u> *Typical spherical aluminum oxide inclusion, left photograph, observed in T-15 alloy, and typical angular silicon oxide inclusion, right photogrph, observed in EX00007 alloy.*



MAGNIFICATION 100X
UNETCHED

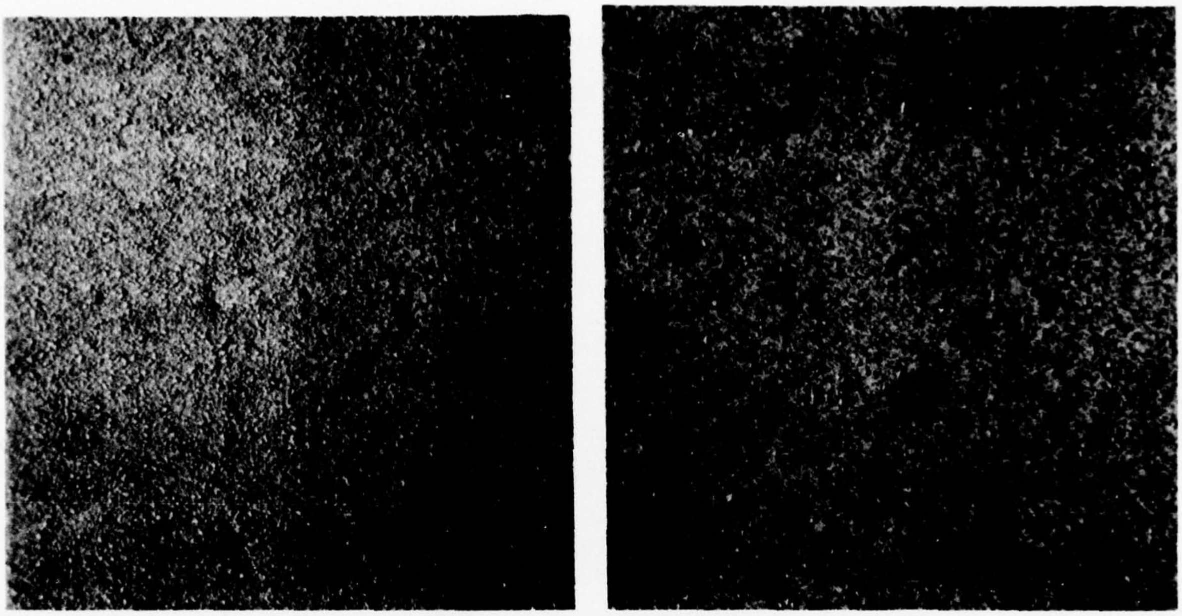
Figure 13 *Powder Metal Processed EX00007 Alloy. The M-50/T-15 powder metal processed alloys were free of non-metallic contamination as was the powder metal processed EX00007 alloy.*



LONGITUDINAL SECTION **UNETCHED**
MAGNIFICATION 500X

TRANSVERSE SECTION **UNETCHED**
MAGNIFICATION 500X

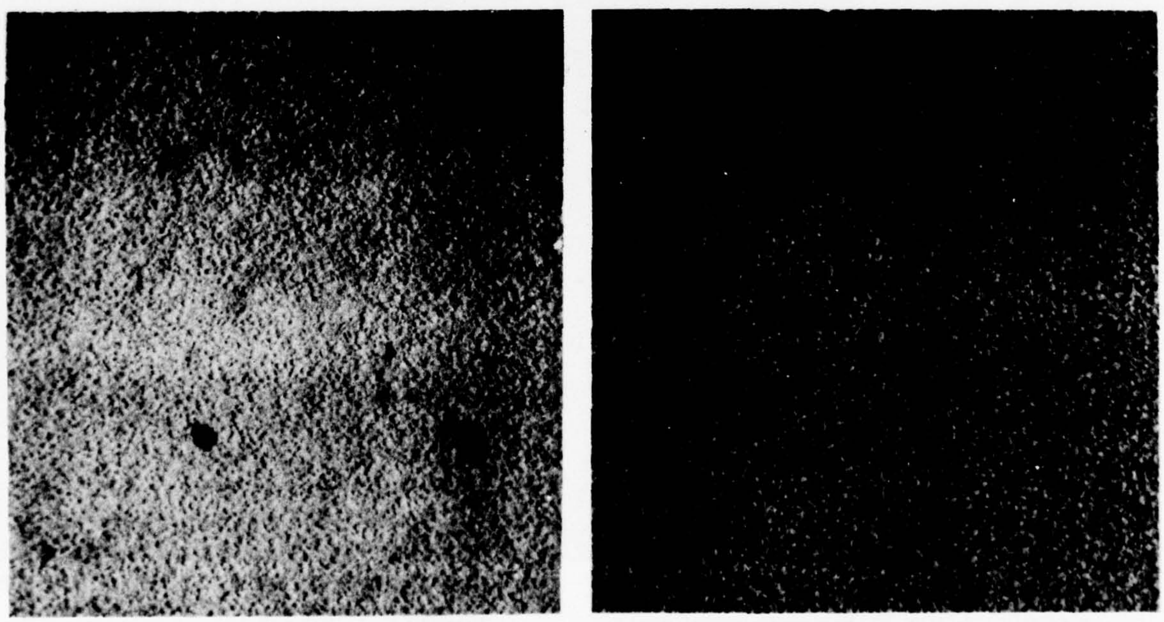
Figure 14 *<u>Powder Processed AISI M-50 Alloy.</u> Worst fields of inclusions as observed in samples of the 13/16" diameter barstock. The larger inclusions were 0.00020" long x 0.00013" wide. Overall the J. K. rating was estimated to be better than 1/2.*



LONGITUDINAL SECTION **UNETCHED**
MAGNIFICATION 500X

TRANSVERSE SECTION **UNETCHED**
MAGNIFICATION 500X

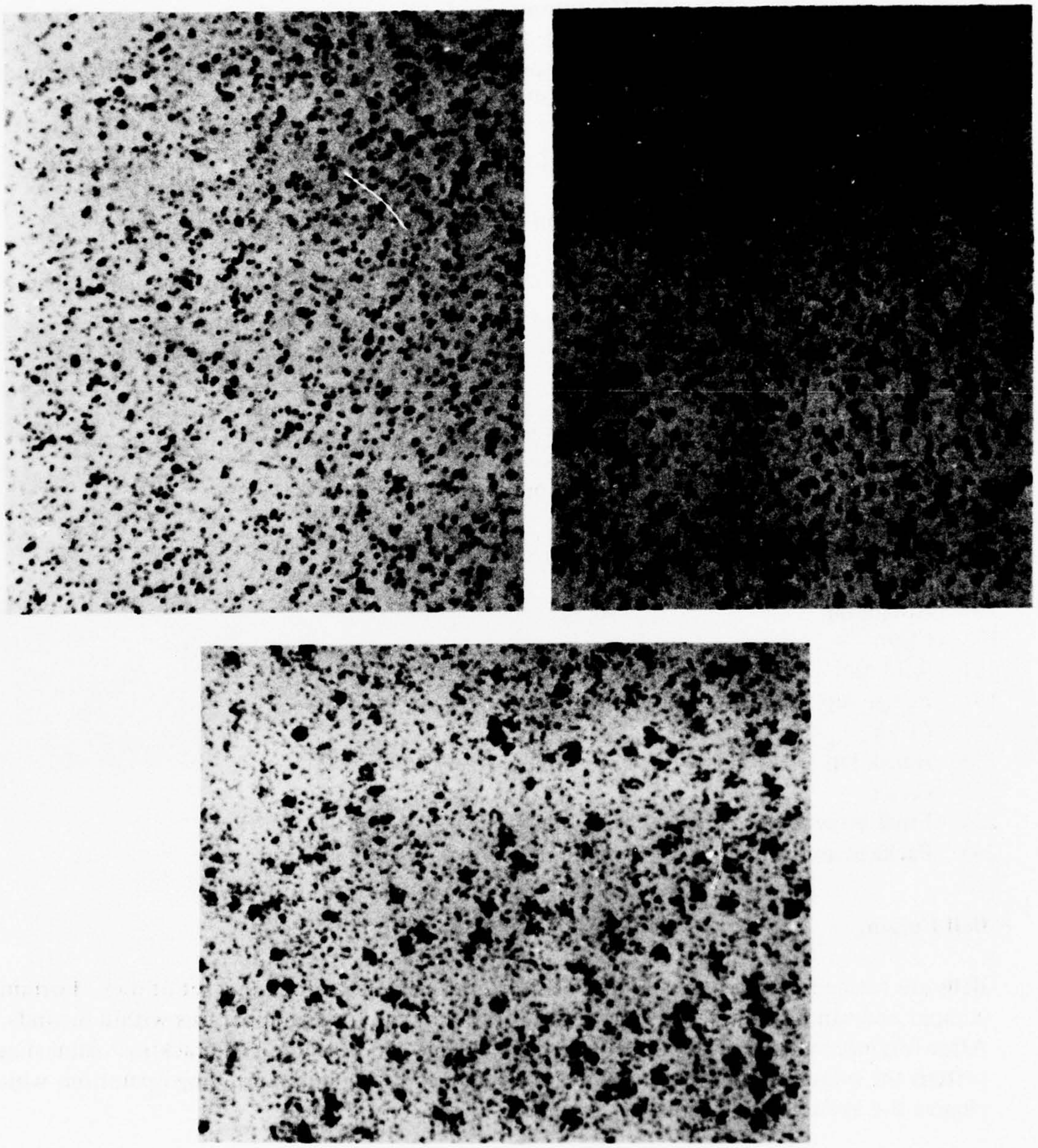
Figure 15 *Powder Processed AISI T-15 Alloy. Worst fields of inclusions as observed in samples of the 13/16 "diameter barstock. The larger inclusions were 0.00025 " long by 0.00019 "wide. Material cleanliness overall was rated better than 1/2 J. K.*



LONGITUDINAL SECTION **UNETCHED**
MAGNIFICATION 500X

TRANSVERSE SECTION **UNETCHED**
MAGNIFICATION 500X

Figure 16 *Powder Processed EX00007 Alloy. Inclusions in this alloy were the largest observed with maximum dimensions of 0.00075" long x 0.00019" wide. The J. K. ratings of this material was considered to be better than 1/2.*



TRANSVERSE SECTION
MAGNIFICATION 1000X
KMnO4 ETCH

Figure 17 *<u>Alloy Microstructures.</u>*
Top Left: Powder Processed AISI M-50 Alloy
Top Right: Powder Processed AISI T-15 Alloy
Bottom: Powder Processed EX00007 Alloy.

Summary of Ball Manufacturing Operations

The manufacturing process used for this program is summarized below to indicate the number of steps involved. The steps are as follows:

1) Hot forge barstock into rough ball form.
2) Anneal
3) Remove metal flash at ball polar and equator regions.
4) Clean
5) Inspect
6) Soft grind
7) Clean
8) Inspect
9) Anneal
10) Separate alloys from 52100 alloy balls.
11) Heat treat to develop final hardness.
12) Inspect for hardness, structure and processing defects.
13) Clean
14) Magnaflux inspect and clean.
15) Final grind
16) Rough lap
17) Clean
18) Acid etch inspect for grinding damage.
19) Rough lap to remove acid etched surfaces.
20) Clean
21) Finish lap
22) Clean
23) Final inspect
24) Package and ship

Ball Forging

Balls are formed by the upset forging of short sections of barstock in a set of dies. Forming is rapid and can be completed with a single stroke of the forging apparatus within seconds. After forging, balls are slow-cooled and then annealed to preclude ball cracking. Annealing softens the material to promote rapid stock removal during initial grinding operations which change the as-forged ball geometry to spheres of uniform diameter.

In order to facilitate forging of 0.750 inch diameter barstock it was necessary to heat the barstock to elevated temperatures. Bars were resistance heated to 1950°F ± 25°F from room temperature within 90 seconds with the equipment shown in Figure 18. Upon reaching the preset forging temperature, as determined by an infra-red sensor, the bars were indexed out of the heating station. They were subsequently moved horizontally through a holding furnace, which maintains bar temperature, and then into the heading machine. This apparatus first sheared a short length off the bar which was then formed into a ball by water-cooled hemispherical dies brought together with a single stroke of the apparatus. The forming rate was approximately 70 balls per minute. The balls were headed to a minimum width of 1.000 inch and a minimum length of 1.020 inch. The as-forged ball exhibited excess material at

regions called polar and equator areas which were a result of the upset forging of the bar-stock. Figure 19 illustrates the as-forged geometry and identifies the polar and equator regions. Two as-forged powder metal processed AISI M-50 balls are shown in Figure 20 to illustrate the as-forged geometry. Upon completion of the forming operations the balls were immersed immediately in a lime media for slow cooling. The as-forged balls were stress relief annealed according to the schedule below:

1. Heat to 1540°F ± 10°F at a rate no greater than 200°F per hour.
2. Hold at maximum temperature for one hour.
3. Cool to 1000°F at a rate of 20°F per hour.
4. Cool from 1000°F with ambient air flow.

Annealing lowers the material hardness to facilitate initial rough grinding processes.

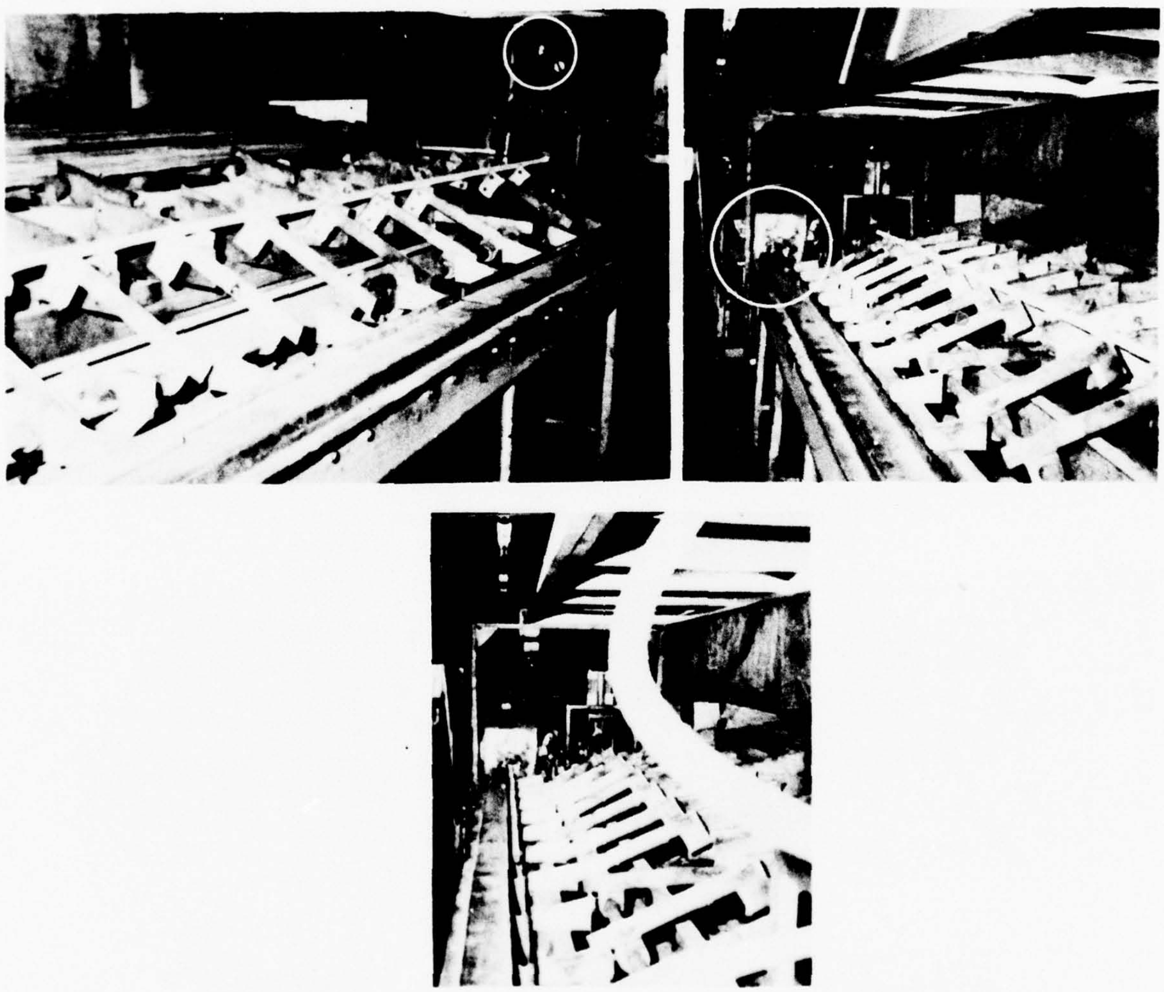


Figure 18 *Resistance Heating of Barstock. (Top Left) This view shows one end of the barstock clamped in one of the electrical leads. An infra-red sensor (circled) monitors bar temperature. (Top Right) This view shows the other electrical connector. After heating, the bar is released to roll down the incline to be moved into the holding furnace (circled). (Bottom Center) The resistance heated bar is shown as it is moved into the holding furnace.*

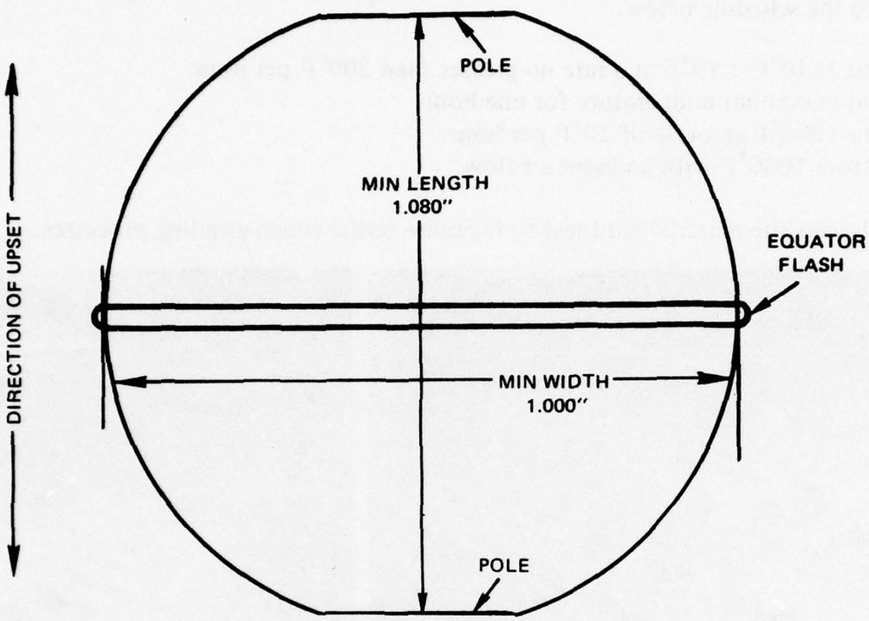


Figure 19 As-Forged Ball Configuration

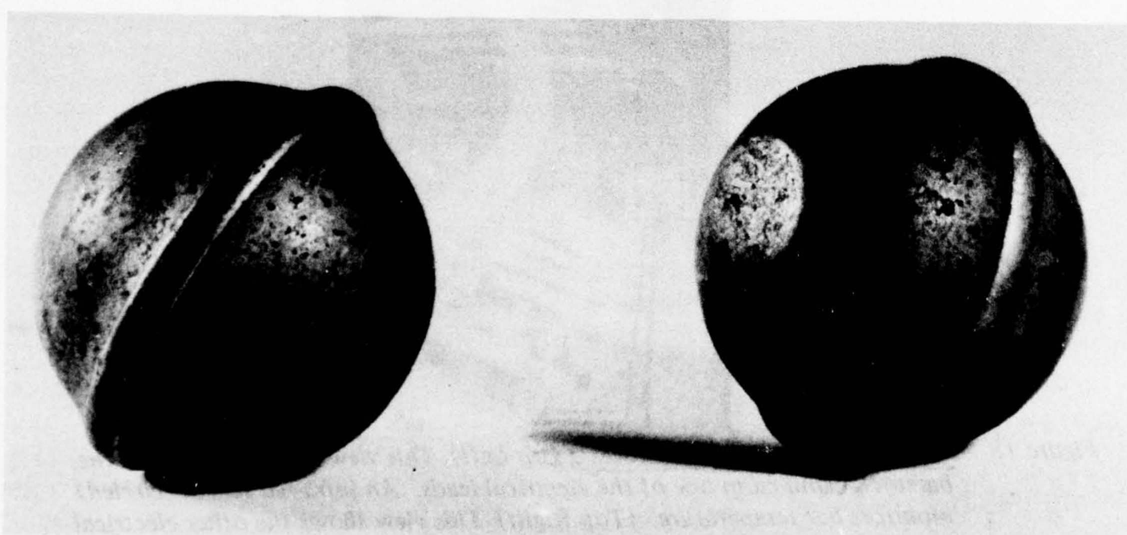


Figure 20 As Forged AISI M-50 Powder Metal Balls. The polar and equator regions are typical. Both balls exhibit oxide scale formed during the high temperature processing.

Ball Grinding

The initial grinding operation removes excess material from the equator and polar regions of the as-forged balls. The as-forged balls are placed between two cast-iron disks. Each disk has a series of concentric grooves which contain the balls. By applying pressure to the plates and rotating the plates, the high points of the balls are worn away resulting in more uniform spheres. A coolant containing a rust-preventative was introduced to the equipment during this operation to moderate material removal. Ball diameters were approximately 0.998 inch after this operation. The balls were tumble cleaned in a mild water-based solvent and then dried in a cobmeal tumble. A random sampling of the balls were hot-acid etched in order to uncover any material or processing defects that may have been present. None were found and the balls were forwarded for continued processing.

The second grinding operation is called soft grind. In this operation a flat 100 grit precision grinding wheel is brought into contact with the balls as they pass through concentric grooves of a 36 inch disk. This device is similar to that used previously except that the power on the main drive is reduced to 30 HP from the 60 HP used to drive the disks in the initial operation. Soft grinding removes all traces of decarburized zones from the balls prior to heat treatment. At this operation, ball diameters are 0.983 inch. The procedure used for cleaning and inspection of the balls is identical to that already described in the previous paragraph. Figure 21 illustrates ball appearance after the initial shaping operations. The balls were relief annealed after soft grind to reduce stresses induced during processing. The relief annealing cycle followed is the same as that described in the Ball Forging section of this report.

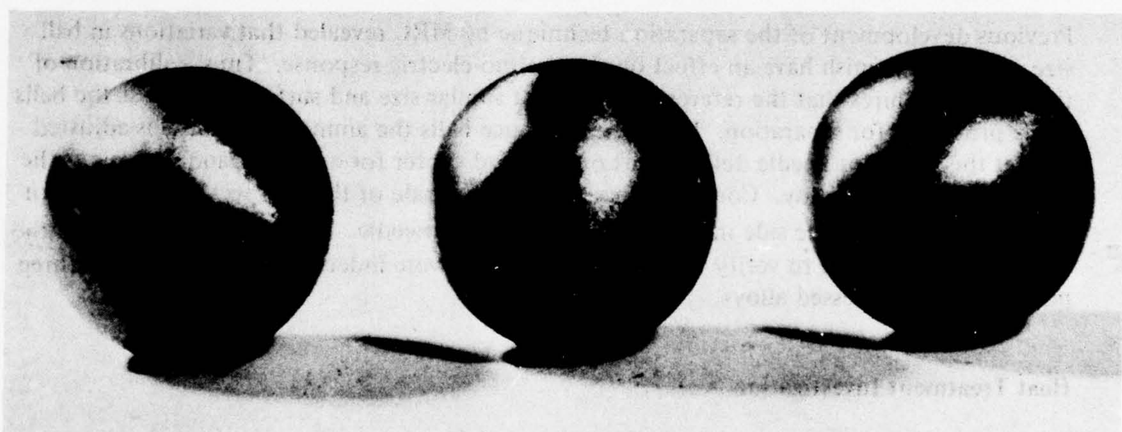


Figure 21 <u>*Soft Ground Balls.*</u> *Soft grinding changes the as-forged geometry to uniform spheres of improved texture.*

Material Separation

The number of balls available for each of the three powder processed alloys was less than the number required to completely fill the ball grinding machines. Therefore, in accordance with the usual practice of the bearing manufacturer, Marlin Rockwell Company, in processing undersized lots, sufficient AISI 52100 alloy balls were added to each lot to fill the grinding equipment. This practice is followed in order to ensure that grinding loads remain constant on each and every ball throughout the grinding cycle. Otherwise, with underfilled units, it would be difficult to guarantee equal spacing between all the balls at all times as they pass through the grinding apparatus. Equal spacing is necessary to obtain equal loading and thus equal and uniform rates of material removal. AISI 52100 alloy balls were used in this capacity for two reasons. First, they were readily available and secondly, and most importantly, they were sufficiently different from the three program alloys in their thermo-electric characteristics so as to permit easy separation by an appropriate discriminator device. Separation was necessary after the rough grinding process so that the materials could be segregated for ball hardening heat treatment.

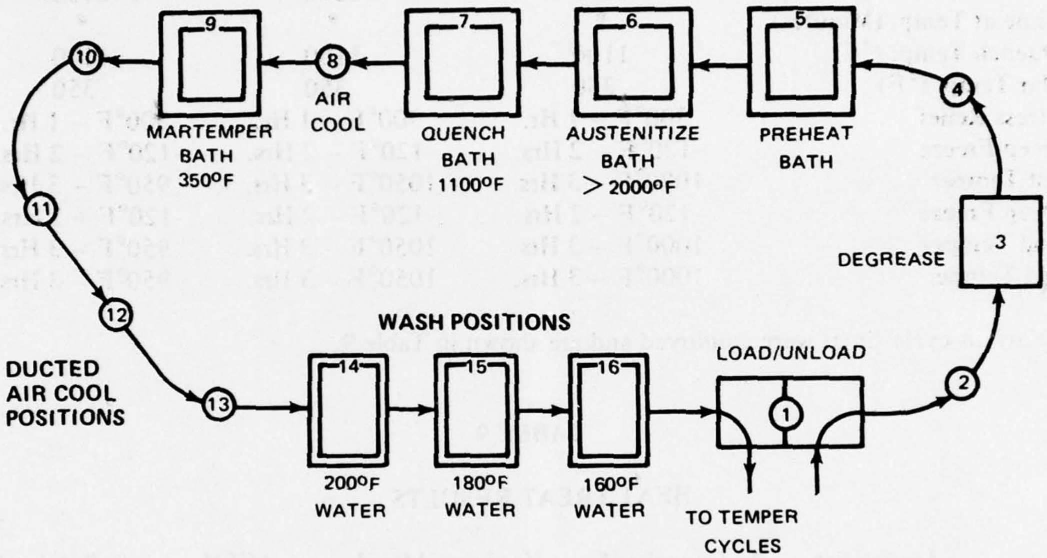
Separation was accomplished with a device that senses the magnitude of current flow resulting from a thermal differential established across the ball. The magnitude of this thermocouple effect varies depending on the chemical composition of the ball being examined. A microammeter in the circuit indicates the level of current flow and different levels indicate different alloys. Prior to initiation of separation operations the system was calibrated with known standards. The standards used were balls of the respective alloys taken from each of the rough ground lots which had been previously identified by means of a standard x-ray fluoresence technique.

Previous development of the separation technique by MRC revealed that variations in ball size and surface finish have an effect on the thermo-electric response. Thus, calibration of the system requires that the reference balls be of similar size and surface texture as the balls being processed for separation. Using the reference balls the ammeter response is adjusted so that the indicator needle deflects left of top dead center for one alloy and deflects to the right for the second alloy. Containers are set on either side of the unit so that the operator can place the ball to the side indicated by the ammeter needle. After the initial pass, all the balls were reinspected to verify that 52100 alloy balls were indeed separated from the three powder metal processed alloys.

Heat Treatment Investigation

After separation from the 52100 balls, the three powder processed alloys were heat treated using MRC's automated salt bath line. This equipment consists of 16 positions which can be indexed automatically at preset cycle rates. The line contains four neutral salt baths utilizing chloride base fused salts for preheat, austenitize and high temperature quench baths and nitrate/nitrite salts for the martemper bath. The set-up is represented schematically in Figure 22. The automated set-up affords the following advantages:

1. Surface protection from decarburization by salt encapsulation.
2. Fast and uniform heating.
3. Minimum residual heat treat stress.
4. Maximum hardness
5. Uniform fine grain microstructure
6. Maximum dimensional stability



SIXTEEN WORK STATIONS ARE INDICATED. TIME AT EACH OPERATION IS PREDETERMINED AND THE BASKETS CONTAINING THE WORK PIECES ARE MOVED AUTOMATICALLY. THE OPERATOR LOADS AND UNLOADS THE BASKETS AND MONITORS TEMPERATURE READOUTS.

Figure 22 Marlin Rockwell Automated Salt Bath Line

MRC used heat treat guidelines in processing the three powder metal alloys which were provided by Carpenter Technology Steel Research Center, the powder metal supplier. The austenitizing temperatures were those suggested by Carpenter. However, MRC modified the secondary or tempering temperatures slightly in order to attain the requisite Rockwell C-62-63 hardness in the alloys. The initial investigation processed short sections of barstock of a size which simulated the ball mass. This was done concurrent with ball processing to expedite the program. Table 8 lists the heat treatment times and temperature employed in processing the bar sections of the alloys.

After completion of the heat treat work certain tests were performed on the samples. The resultant data for hardness, grain size and retained austenite, as a result of different times in the austenitize salt bath, are presented in Table 9.

TABLE 8

HEAT TREATMENT OF POWDER PROCESSED ALLOY BALLS

Alloy	M-50	T-15	EX00007
Preheat Temp. (°F)	1550	1550	1550
Austenitize Temp. (°F)	2050	2250	2100
Time at Temp. (Minutes)	*	*	*
Quench Temp. (°F)	1100	1100	1100
Mar Temp. (°F)	350	350	350
Stress Relief	300°F – 1 Hr.	300°F – 1 Hr.	300°F – 1 Hr.
Deep Freeze	–120°F – 2 Hrs.	–120°F – 2 Hrs.	–120°F – 2 Hrs.
1st Temper	1000°F – 3 Hrs.	1050°F – 3 Hrs.	950°F – 3 Hrs.
Deep Freeze	–120°F – 2 Hrs.	–120°F – 2 Hrs.	–120°F – 2 Hrs.
2nd Temper	1000°F – 3 Hrs.	1050°F – 3 Hrs.	950°F – 3 Hrs.
3rd Temper	1000°F – 3 Hrs.	1050°F – 3 Hrs.	950°F – 3 Hrs.

*Various cycle times were employed and are shown in Table 9.

TABLE 9

HEAT TREAT RESULTS

Alloy	Austenitize Time (Min).	As-Quenched* Hardness (Rc)	Hardness After* Temper (Rc)	ASTM Grain Size	% Retained Austenite
M-50	4	63.8	63.4	12.5	<3
	5	63.9	62.9	12.5	<3
	5 ½	63.6	63.2	12.5	<3
	6	63.8	63.2	12.5	<3
	7	63.5	63.3	12.5	<3
T-15	3	66.0	63.1	12.5	<3
	3½	66.3	63.0	12.5	<3
	4	Not Taken	63.1	12.5	<3
	5	65.3	63.2	12.5	<3
	7	64.2	62.4	12.5	<3
EX 00007	3	58.8	63.3	11.5	<3
	7	55.3	62.5	11.5	<3
	10	54.8	62.4	11.5	<3
	15	56.9	62.7	11.5	<3
	30	55.4	62.4	11.5	<3

*Average of Three Readings.

The microstructures of the three alloys were so uniform that grain fiber flow or directionality normally observed in conventionally processed bearing steels could not be discerned in any of the barstock samples microexamined in this study. The uniform distribution of the refined carbides was impressive. Grain size was similarly refined. All the microstructures exhibited grain sizes finer than the requisite ASTM #10 rating which had been established previously as the maximum allowable. Photomicrographs of the three powder prepared alloys are shown in Figures 23, 24 and 25, which also include, for comparison, microstructures typical of that which is developed in the given alloy when conventionally processed. The uniformity and refinement of carbides in the powder processed steels is striking.

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MAGNIFICATION 1000X

Figure 23 *AISI M-50 Steel Fully Heat Treated. (Left) Powder Metal Processed, (Right) Conventionally Processed*

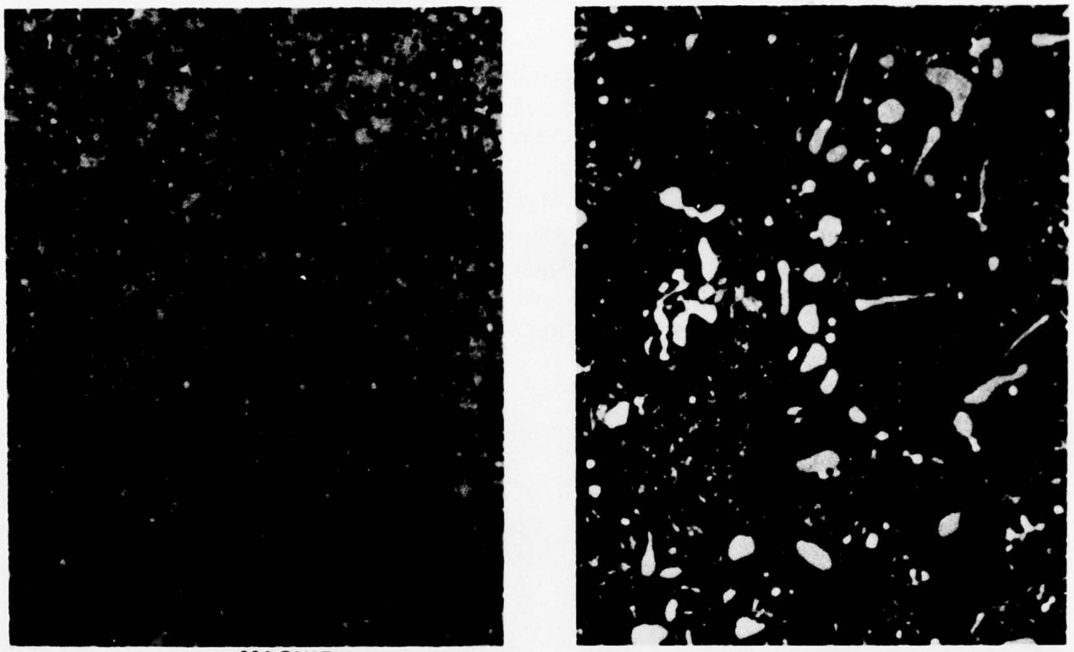

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Figure 24 <u>*AISI T-15 Steel Fully Heat Treated.*</u> *(Left) Powder Metal Processed, (Right) Conventionally Processed*

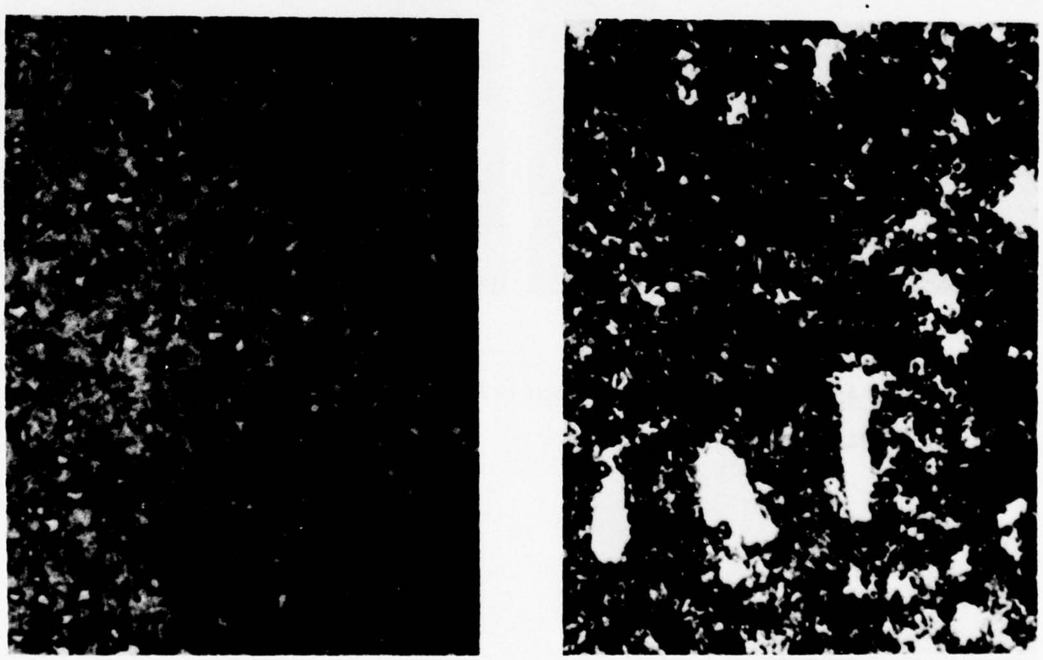

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Figure 25 <u>*EX 00007 Steel Fully Heat Treated.*</u> *(Left) Powder Metal Processed, (Right) Conventionally Processed*

Ball Heat Treatment

MRC selected austenitize times of 6-1/4 minutes for processing of the M-50 and T-15 alloy balls. EX00007 processing utilized a 20 minute austenitize cycle. All the other steps in the heat treat processing of the balls was consistent with the information presented in Table 8.

After processing, several balls were taken from each group for hardness determination purposes. Three hardness readings were taken on parallel sections machined on the balls. One test rod of each alloy which was processed with the ball lots was also examined for hardness. The results are presented in Table 10.

TABLE 10

ALLOY HARDNESS

Alloy	Ball Hardness* (Rc)	Rod Hardness* (Rc)
AISI M-50	62.2	62.1
AISI T-15	62.9	62.7
EX00007	62.9	62.8

*Average of three readings.

Examination of the as tempered balls for retained austenite, utilizing x-ray diffraction techniques, revealed that the AISI M-50 and AISI T-15 exhibited less than 2% content with the EX00007 alloy revealing less than 3%. These levels were judged acceptable and the balls were subsequently forwarded for final finishing operations.

Final Finishing

After heat treatment, the balls were inspected by acid etch and magnaflux techniques to evaluate ball quality. All the acceptable balls were then final ground in equipment that was identical to that used for soft grind processing. Sufficient material was removed so as to eliminate any decarburization that could have occurred during the heat treat cycle. After final grinding, ball diameters were checked to ensure that the balls were of uniform size. The balls were then rough lapped as the next step in the surface finish improvement process. After rough lapping the balls were cleaned in preparation for the acid etch inspection operation. This time, all the balls were acid etched in order to cull out those balls with damaged surfaces. Accepted balls were cleaned and then were returned to the rough lap equipment in order to remove the layer of acid etched material. Less stock was removed in this cycle than occurred in the first rough lapping process. The balls were cleaned again and final lapped to the desired finished surface. Subsequent visual inspection of the balls eliminated those which exhibited defects. Accepted balls were finally dipped in a rust preventative oil bath and then packaged for shipment.

POWDER METAL BALL DIMENSIONAL QUALITY DETERMINATION

Representative samples of the powder metal balls were inspected for roundness and surface finish. Ball quality was previously specified to conform to the Anti-Friction Bearing Manufacturers Association (AFBMA) Grade 10 requirements. This standard specifies that the diameter or sphericity tolerance per ball not exceed 0.000010 inch and that the ball surface exhibit a finish no greater than 1 microinch (AA).

Inspection revealed that the powder metal balls met the AFBMA Grade 10 roundness requirement but exceeded the surface finish requirement in that surface finishes of 2 to 3 microinches AA were observed. The powder metals apparently responded to the routine finishing operations in a manner that differed somewhat from that normally achieved with conventionally manufactured materal. Typical traces of the ball roundness are presented in Figures 26, 27 and 28. For comparison, the trace of a VIM-VAR M-50 ball, supplied by another vendor is shown in Figure 29. Surface finish of the VIM-VAR M-50 ball is presented in Figure 30 and demonstrates compliance with the AFBMA Grade 10 surface finish requirement. Results of similar measurements of the powder metal balls, presented in Figures 31, 32 and 33, indicate surface roughness levels slightly above the target one microinch AA finish.

The balls were not submitted for relapping to avoid the possibility that subsequent processing for improvement of surface finish might have a negative effect on the roundness characteristics of the balls. It was also thought that the effect of a 2 or 3 microinch finish on subsequent fatigue life performance could prove moot when ball roundness was excellent. Therefore the balls were accepted "as is" for subsequent single ball fatigue testing.

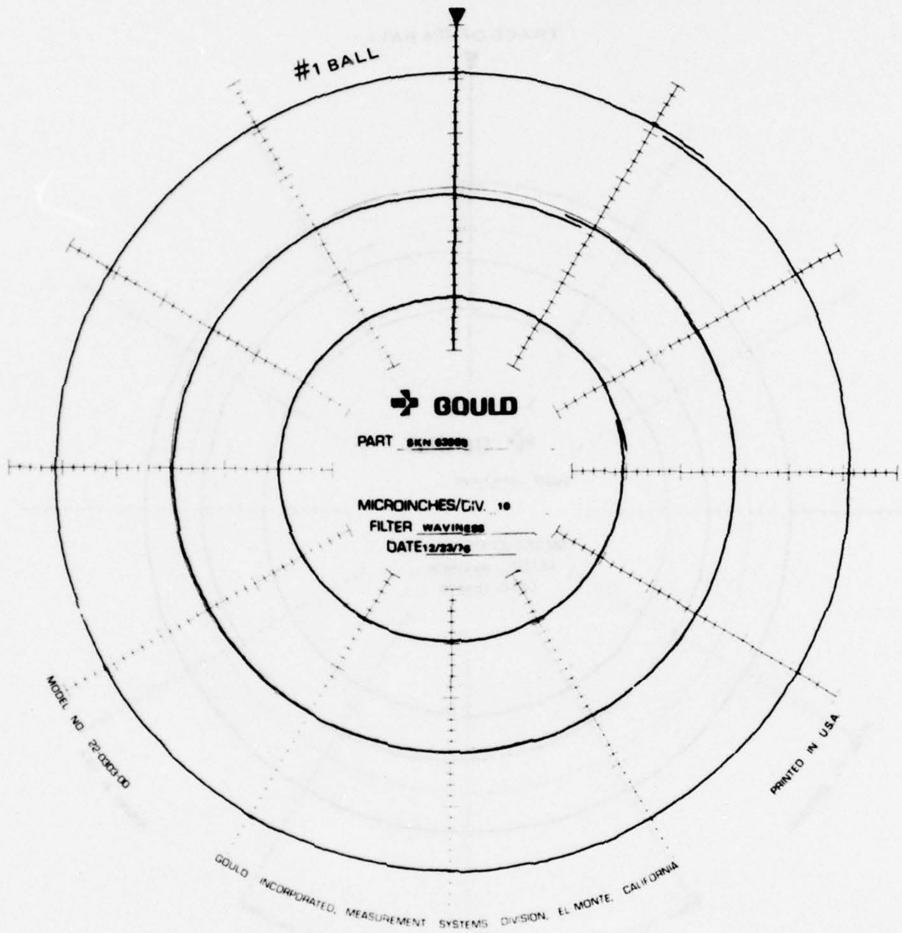

Figure 26 *<u>Typical Ball Roundness, P/M M-50.</u> Traces in 3 planes reveals roundness to be within 10 microinches AA.*

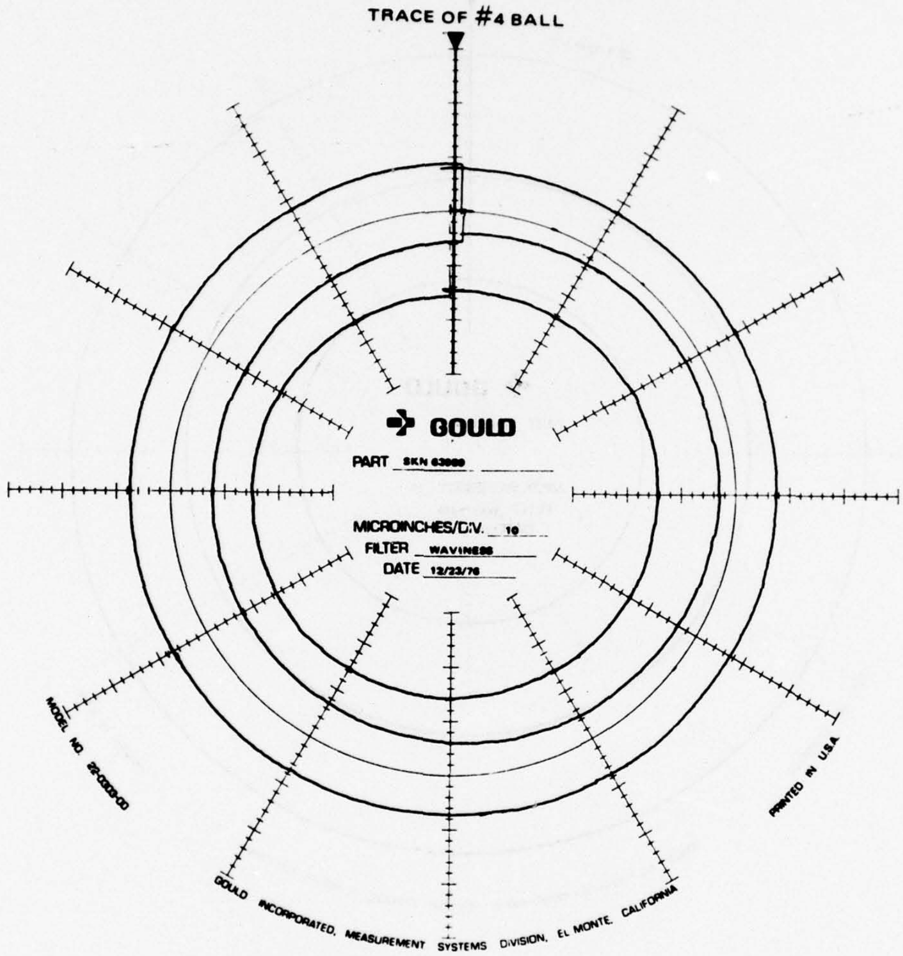

Figure 27 ***Typical Ball Roundness, P/M T-15.*** ***Traces in three planes reveals roundness to be within 10 microinches AA.***

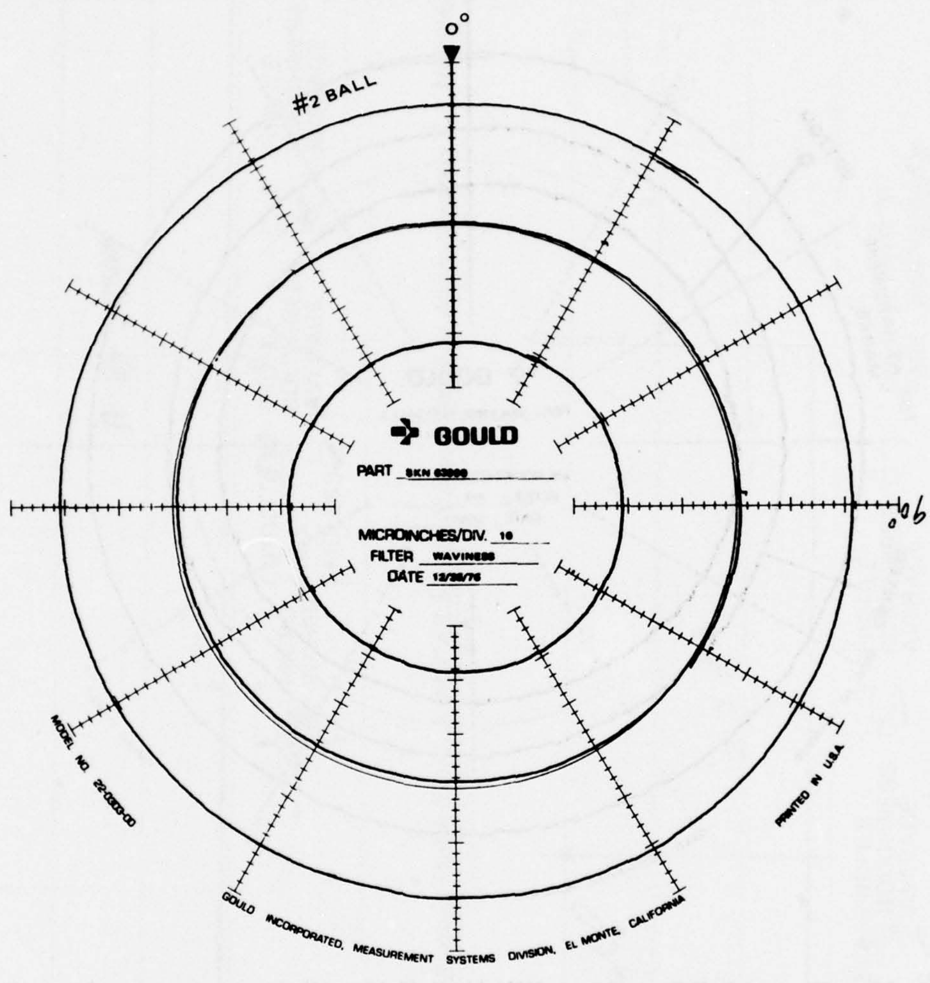

Figure 28 ***Typical Ball Roundness, P/M EX00007.*** ***Traces in three planes reveals roundness to be within 10 microinches.***

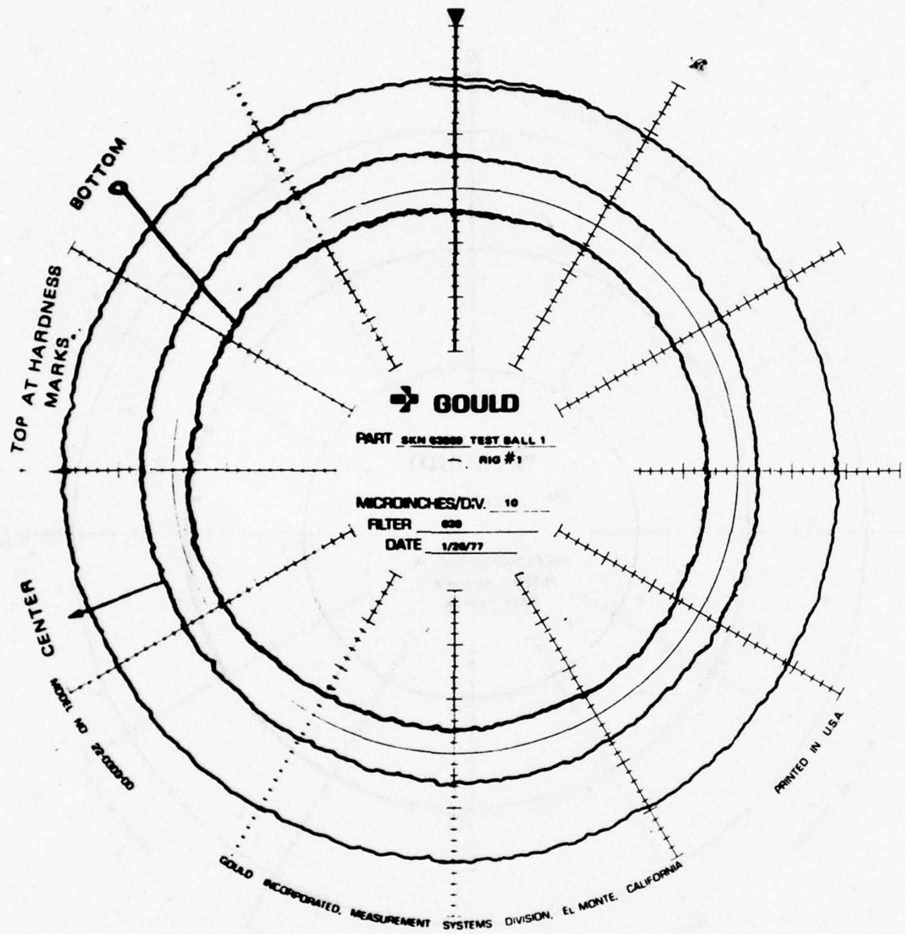

Figure 29 ***Typical Ball Roundness, VIM-VAR M-50.*** ***All three traces reveal roundness to be within 10 microinches AA.***

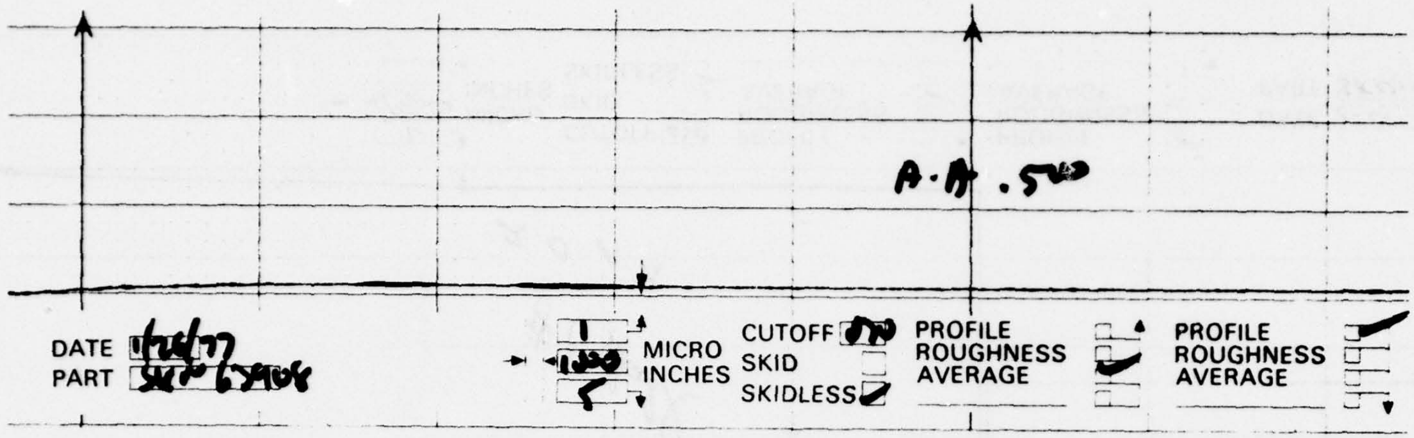

Figure 30 ***Typical Ball Surface Finish Trace, VIM-VAR M-50. Surface Finish is Approximately 0.5 Microinch AA.***

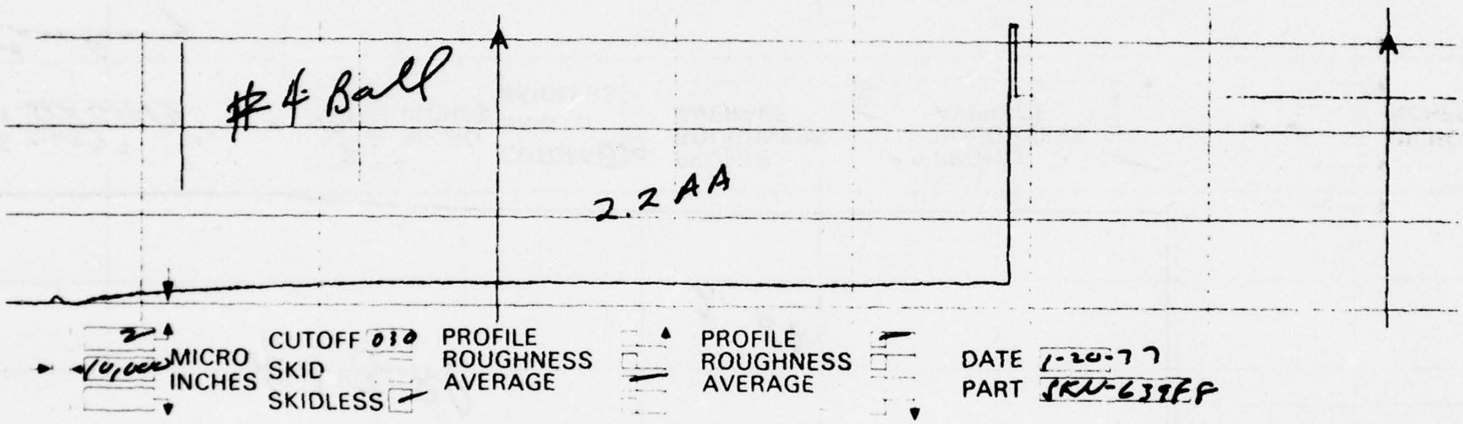

Figure 31 ***Typical Ball Surface Finish Trace, P/M M-50. Surface Finish is Approximately 2.2 Microinch AA***

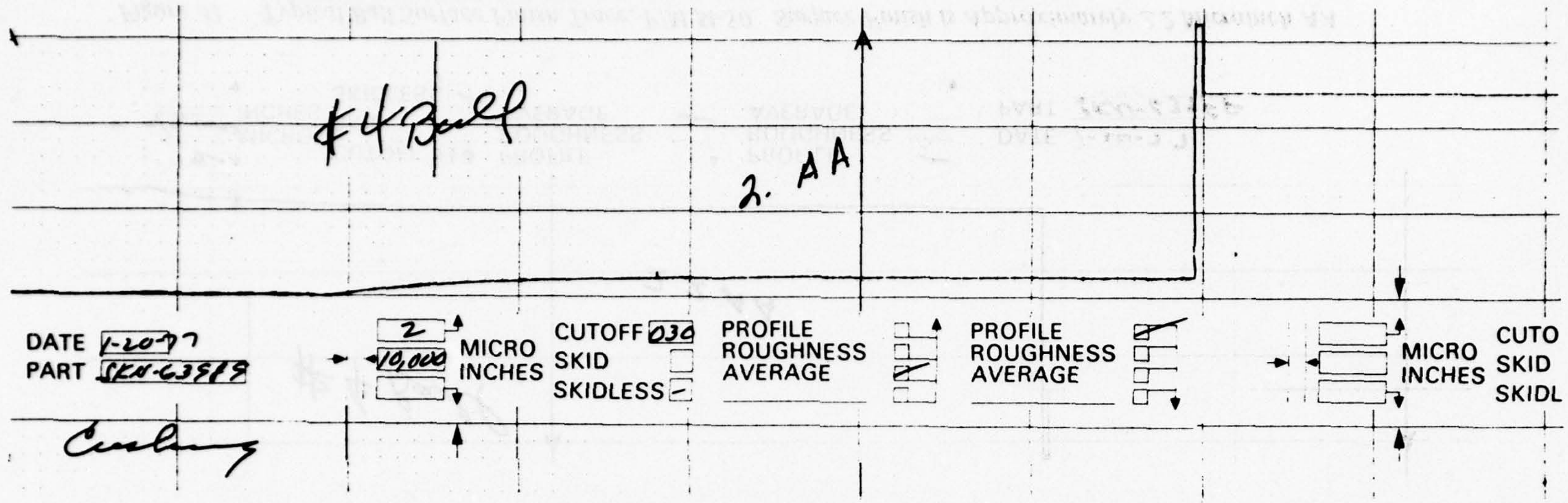

Figure 32 Typical Surface Finish Trace, P/M T-15. Surface Finish is Approximately 2.0 Microinch AA.

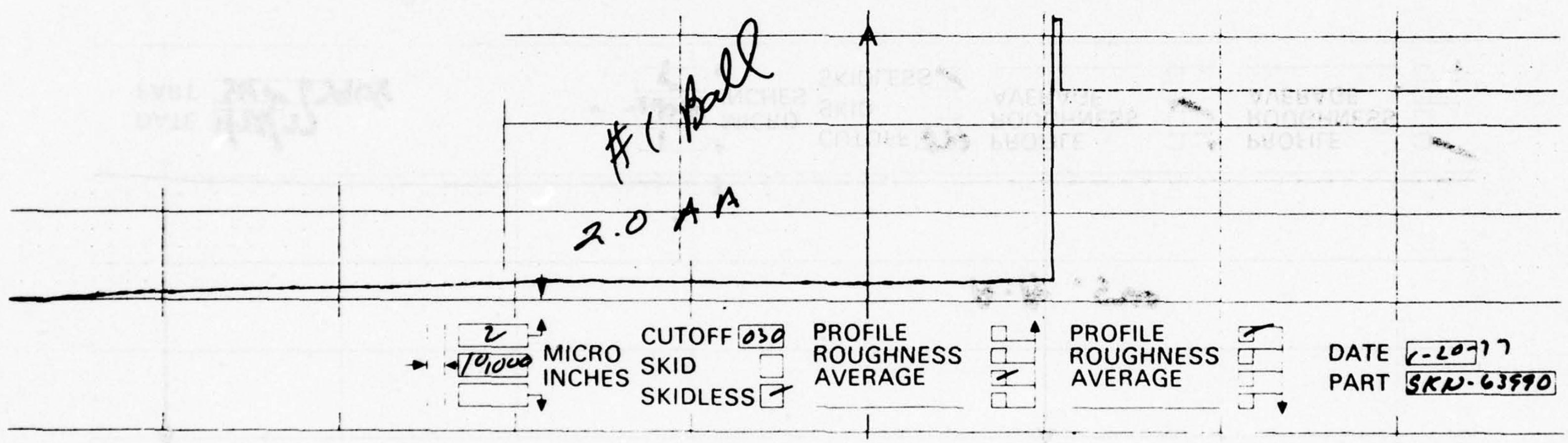

Figure 33 Typical Ball Surface Finish Trace, P/M EX00007. Surface Finish is Approximatley 2.0 Microinch AA.

SECTION III

EXPERIMENTAL PROGRAM

ROLLING CONTACT FATIGUE TESTS

In order to evaluate the potential of powder metal balls for use in aircraft gas turbine engine bearings, dynamic ball tests were conducted to determine fatigue life. Tested balls were then subjected to detailed metallurgical examination in an attempt to reveal failure modes.

THE SINGLE BALL TEST RIG

The usual practice in dynamic ball-testing at Pratt & Whitney Aircraft is to load individual balls in compression between two rotating V-grooved races in test rigs of the type illustrated in Figure 34. The test load is of a magnitude encountered in bearing operation, but the stress induced at the ball-race contact zones is much higher with the V-grooved rig races than with normally contoured bearing races. This produces relatively rapid ball failures and provides a convenient way of comparing ball materials, surface finishes, and other variables that affect ball fatigue life. Test data is evaluated by statistical means to ensure that any observed apparent differences are real.

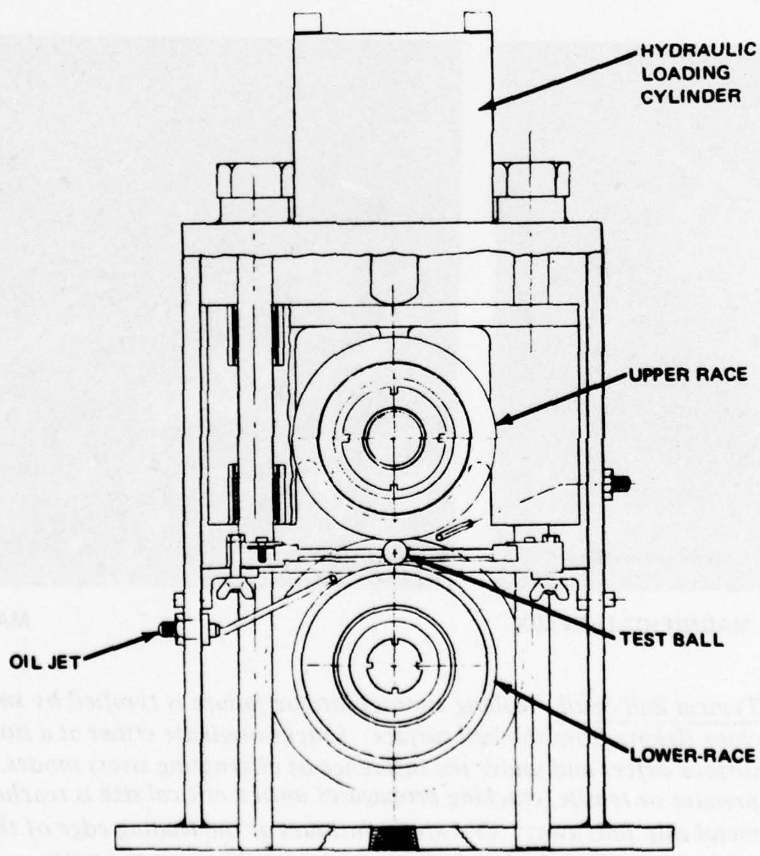

Figure 34 ***Single Ball Fatigue Test Rig.*** *Test ball is driven by the lower hub; ball loading is accomplished through the hydraulically loaded upper hub assembly. Oil jets above and below the ball provide flood oil lubrication.*

Ball failure; that is, spalling of the ball surface as illustrated in Figure 35, or successful completion of a 40 hour test period constitutes termination of a test. After completion of at least ten tests, or as many as twenty, for a given ball lot the data are reduced by Weibull analysis techniques. This is done to determine the B-10 fatigue life of either the subject ball material, the ball processing method or the test lubricant.

The single ball test rigs have proven to be highly consistent in their ability to properly rank materials, processes and lubricants as to their influence on bearing fatigue life. This ability of the single ball tester is considered to be a direct result of careful attention to the development of ball-ring contact conditions that simulate the application. The vee groove geometry of the matching rings that the ball rides on imparts a spin-roll ratio action tailored to match average conditions encountered in main shaft jet engine angular contact ball thrust bearings. Also, the control of both the lubrication and the surface topography of the vee rings to simulate that encountered in the bearing application are factors of no small consequence. A specific example of how the single ball tester can relate to real bearings has been well illustrated in work reported by the Coordinating Research Council in Reference 2.

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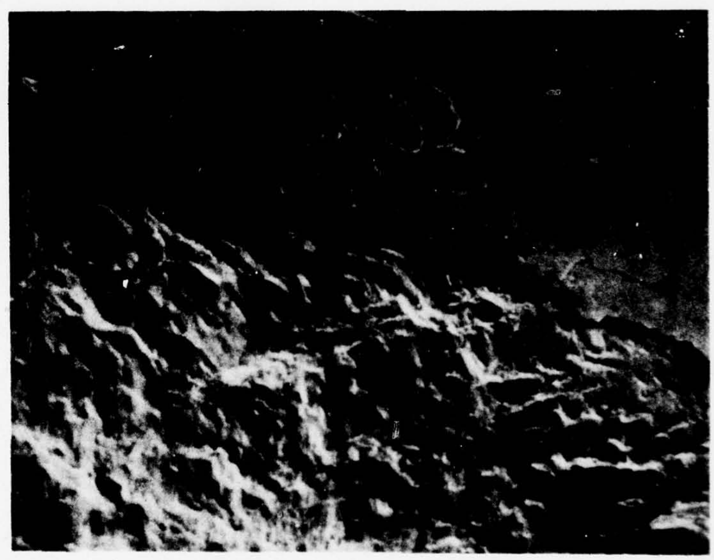

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Figure 35 *Typical Ball Spall. Rolling contact fatigue failure is typified by small metal chips flaking from the ball surface. Cracks originate either at a surface or subsurface defect and under the influence of alternating stress modes, either compressive or tensile, cracking propagates until a critical size is reached and a metal chip falls away. Cracking continues at the leading edge of the spall, as shown in the right hand photo, and contributes to the propagation of spall damage. Arrow indicates leading edge of the spall.*

Reference 2 describes a program whereby three different lubricants were evaluated to determine their effect on the fatigue life of SAE 52100 bearing steel. Five different laboratories using four different element testers ran controlled tests on each of the same three lubricants. The results were then compared to data previously obtained from fatigue life tests conducted on full scale main shaft ball thrust bearings made of the same material, SAE 52100. The single ball testers ranked the three oils in the same order as that resulting from the full scale bearing tests, as shown in Table 11 below. Two of the three other elemental testers also ranked the oils in the proper order. However, the single ball testers were unique in that they produced a relative B-10 life rating of the 3 oils that agreed precisely with those ratings obtained from the full scale bearing life data.

TABLE 11

OIL-TO-OIL B10 LIFE RATIO COMPARISON (WITHIN LABORATORY)

	RAO-8-64	RAO-10-64	RAO-9-64
Barwell 4-Ball	1	1.1	0.4
3-Ball/Cone	1	0.9	1.1
Rod/Crowned Cylinders	1	2.4	7.6
3-Ball/Cone	1	6.3	54.0
P&WA Single Ball	1	1.5	4.5
Full-Scale Bearings	1	1.5	4.5

Single ball fatigue testers have been employed extensively as a screening device to evaluate materials that appear to have potential use in aircraft engine bearings. What is sought is a material that produces a single ball tester B-10 life that is better than currently used materials by a factor of 2 or more. A considerable data bank exists on the single ball fatigue life of most materials that have been considered seriously by the industry for possible end use in bearings. This data has been used for comparative purposes in making an assessment of the performance of the powder processed products investigated in the subject program. Some of this data has been published in the open literature and is contained in References 3 and 4.

In every case, where subsequent full scale bearing endurance testing was conducted, the resultant B-10 lives were found to rank in the same order as that previously achieved in single ball testing. This has been borne out in comparing the effects of other variables as well as for bearing alloys. These variables include surface finish, hardness, lubricants, oil temperature and melting processes. Current main shaft engine bearing materials, design and purchasing specifications for production hardware are a direct reflection of results obtained from the single ball testing program.

TEST BALL CONFIGURATION

Parallel flats were machined on the balls to provide a configuration as shown in Figure 36. During testing, gyroscopic forces kept the flatted ball tracking continually over the same region and the material fatigued much more quickly than when tested in the spherical configuration. Spherical balls reoriented periodically during test and effectively distributed stress cycles over more of the ball surfaces resulting in long fatigue life which unnecessarily extended test time.

The machined flat provides a convenient surface for determining ball hardness as illustrated in Figure 37 which shows impressions made by the hardness indenter on a flatted ball.

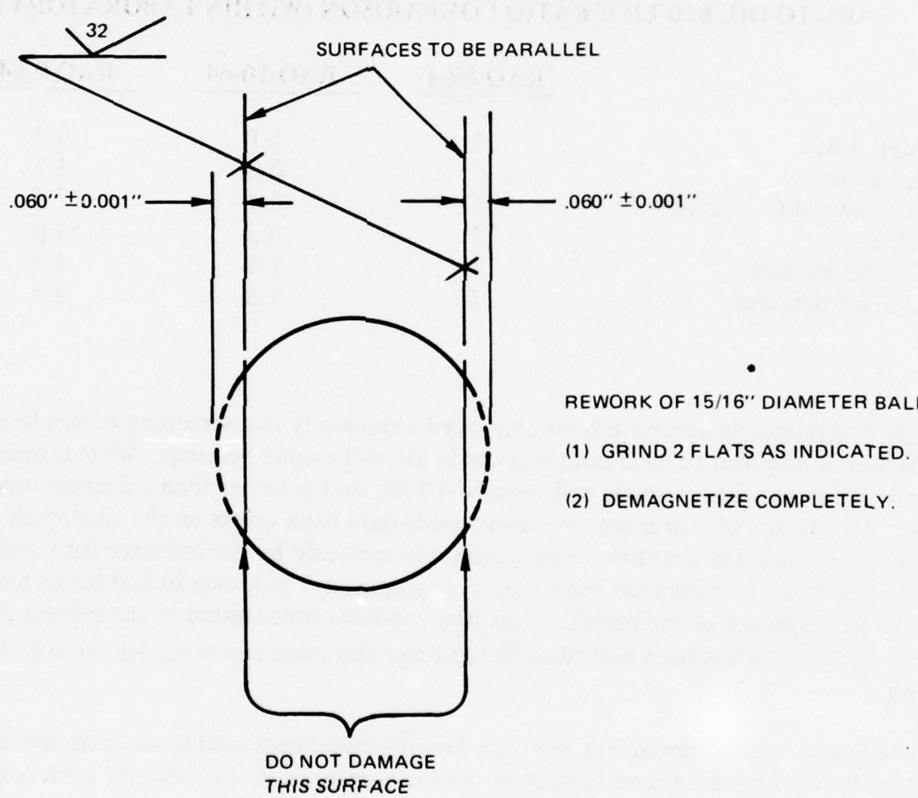


Figure 36 Flatted Ball

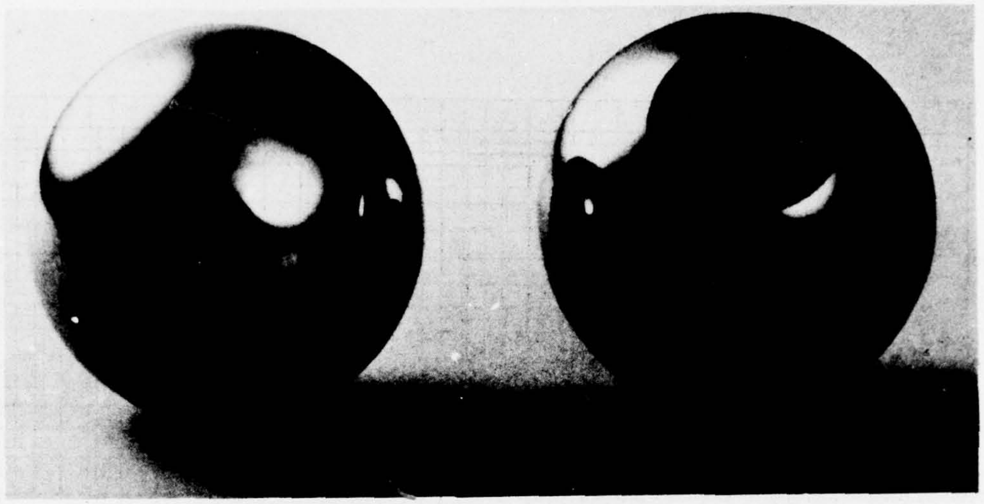


Figure 37 *Test Balls. An as-processed ball (left) and a flatted ball are shown. Impressions made by the Rockwell machine indenter are evident on the machined flat. Ball hardness is ascertained prior to testing.*

BALL FATIGUE TEST CONDITIONS

A 0.9375 inch diameter ball was tested at a load of 1350 pounds to develop a maximum Hertz stress of 600,000 psi at the ball race contact area. This stress level was sufficient to cause spall failure within a few hours but was below the threshold stress of plastic deformation. MIL-L-7808G oil heated to 300°F was supplied to the ball/race contacts. Test races were driven at 7800 rpm which spun the test ball at 41,050 rpm. Race surfaces were honed to a nominal 5AA microinch finish. Ball surfaces were 3AA or better. Oil film protection was marginal under the imposed loads and speeds; balls normally failed in a matter of hours.

VIM-VAR M-50 STEEL TEST RESULTS

On the basis of single ball test experience, P&WA selected VIM-VAR M-50 steel to establish the baseline fatigue life for this program. Over the course of several years VIM-VAR M-50 steel has been tested repeatedly in the single ball rigs to confirm repeatibility of rig performarrce and that of the associated equipment and related test procedure. The results were consistently long lived. These previous tests had been conducted in MIL-L-23699 lubricant. For the subject program VIM-VAR M-50 balls, processed to Rockwell C62-63 hardness, were tested in the Air Force supplied MIL-L-7808G lubricant in order to establish the fatigue life baseline of this ball material and lubricant couple.

Testing of VIM-VAR M-50 flatted balls produced fifteen spall failures. Ball lives ranged from 13.5 million to 149.2 million stress cycles. Ball tests lives, median rank, serial number and ball hardness of the 15 flatted balls are shown in Table 12. The resulting Weibull curve is presented in Figure 38.

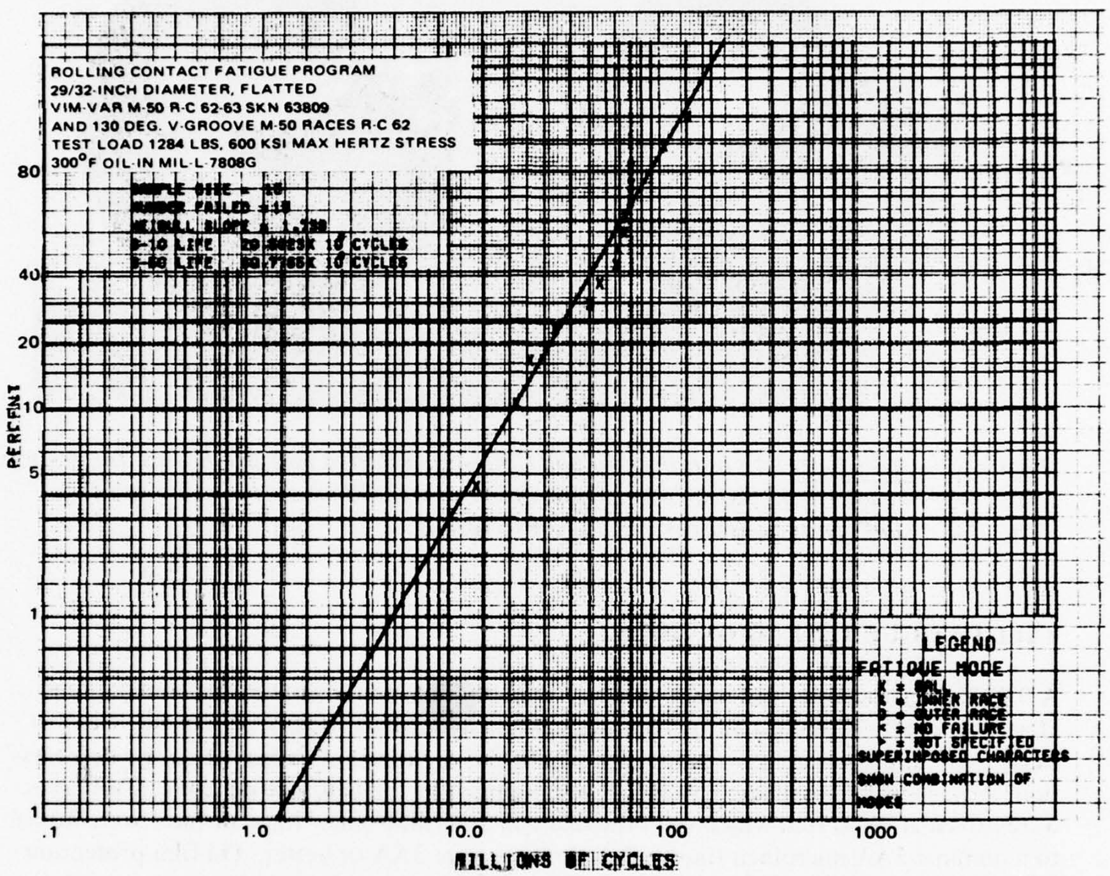


Figure 38 *Weibull Curve of VIM-VAR M-50 Ball Test Results. A B-10 life of 20.56 x 10^6 stress cycles was observed for this population.*

TABLE 12

VIM-VAR M-50 BALL DATA

BASELINE BALLS FOR POWDER PROCESSED BEARING STEEL PROGRAM

Ball Life Millions of Stress Cycles	Median Rank	Rc Hardness (Avg. of 3 Readings)	Test S/N
13.5	0.04516	61.7	15
21.4	0.11014	62.5	23*
25.0	0.17511	63.4	16
33.3	0.24009	63.1	17
49.1	0.30507	62.8	9*
54.8	0.37005	63.1	12*
66.7	0.43502	62.8	8
68.1	0.50000	63.0	11
72.6	0.56498	62.8	6
74.4	0.62995	63.0	27
77.9	0.69493	63.1	10
78.5	0.75991	63.1	18
79.2	0.82489	63.3	28
114.3	0.88965	62.7	24*
149.2	0.95484	62.8	19*
	Requested Ball Hardness	Rc 62 ±1	

*Balls submitted to the metallurgical lab for examination.

This performance of 20.6 million stress cycles is outstanding compared to results obtained previously. Prior tests of M-50 steel in the flatted configuration typically produced B-10 life values between 5.8 to 10.1 million stress cycles. This baseline life value that is twice that which had been observed previously for M-50 steel presents a standard that will require exceptional performance from the powder metal prepared alloys if they are to qualify for further evaluation in full scale bearings.

POWDER METAL PROCESSED M-50 TEST RESULTS

In keeping with the requirements of the contract, 30 test points were obtained. All the balls spalled with test lives ranging from 13.0 million to 123.8 million stress cycles. These data are presented in Table 13 along with median rank, test serial number and ball hardness information. The test results produced the Weibull curve shown in Figure 39. The B-10 life of 16.99 million stress cycles thus obtained compares to 20.56 million cycles for conventionally cast and processed VIM-VAR M-50 baseline material. Applying L. G. Johnson's (Ref. 1) technique for the statistical comparison of B-10 life values, it was determined that there is only 60% confidence that these lives are significantly different. This low confidence means that the lives are essentially the same. Thus, the performance of this P/M M-50 does not appear to be any better or any worse than that of the VIM-VAR M-50, at least as determined by means of the single ball rolling contact fatigue test.

TABLE 13

POWDER METAL M-50 BALL DATA

Ball Life Millions of Stress Cycles	Median Rank	Rc Hardness (Avg. of 3 Readings)	Test S/N
13.0	0.02284	62.3	2*
16.1	0.05575	62.0	9*
17.3	0.08866	62.3	47*
18.4	0.12156	62.3	50*
20.4	0.15447	62.3	21*
22.9	0.18738	62.4	26
26.1	0.22029	62.7	27
26.7	0.25319	62.7	28
26.8	0.28610	62.4	38
27.7	0.31901	62.9	13
32.3	0.35192	62.5	8
34.1	0.38482	62.3	7
35.1	0.41773	62.4	18
37.1	0.45064	62.3	45
40.1	0.48355	62.4	22
41.4	0.51645	62.4	3
42.0	0.54936	62.2	30
46.1	0.58227	62.2	39
47.6	0.61518	62.2	32
50.8	0.64808	62.5	36
53.6	0.68099	62.3	10
54.3	0.71390	62.5	34
62.1	0.74681	62.9	35
63.4	0.77971	62.3	51
68.8	0.81262	62.0	40
68.9	0.84553	62.3	46*
86.1	0.87844	62.4	43*
108.3	0.91134	62.3	33*
108.7	0.94425	62.5	37*
123.8	0.97716	62.4	41*
	Requested Ball Hardness	Rc 62 ±1	

***Balls submitted to the metallurgical laboratory for examination.**

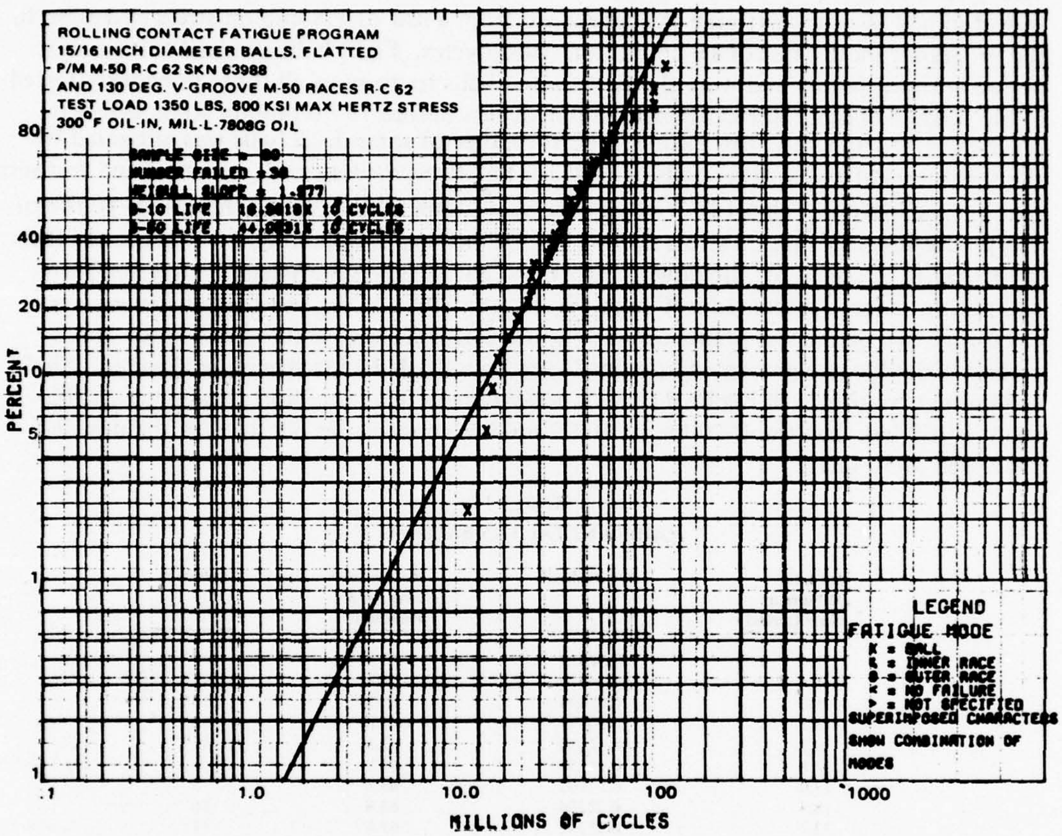


Figure 39 *Weibull Curve of Powder Metal Prepared M-50 Ball Test Results. A B-10 life of 16.99 x 10^6 stress cycles was observed for this population.*

POWDER METAL PROCESSED T-15 TEST RESULTS

Thirty four valid tests points were obtained for the evaluation of the P/M T-15 balls. The spread in ball lives was extreme as lives ranged from a low of 1.4 million stress cycles up to the program runout limit of 197.6 million stress cycles. Eight balls survived this runout period without failure and were the first flatted balls to do so of all those previously tested in the single ball rigs. Normally ball spalling occurs before 197.6 million stress cycles is reached. Unfortunately, this excellent performance of some T-15 balls was mitigated by the short lives of many other balls in this lot. Ball lives, median rank, hardness and test serial number are listed in Table 14. Weibull analysis of these data revealed that the B-10 life of this group was 6.67 million stress cycles. This value is approximately 2.5 times lower than the B-10 life obtained for the powder processed M-50 balls. The Weibull curve for T-15 ball performance is presented in Figure 40. Examination of the test data in Table 14 revealed that two of the test points occurred quite early. These points were deleted and a second Weibull curve generated in order to see how the B-10 life would be affected. The resultant curve shown in Figure 41 yields a B-10 life of 13.14 million stress cycles. This result is still less than the B-10 life of 16.99 million stress cycles obtained in the powder processed M-50 tests.

TABLE 14

POWDER METAL T-15 BALL DATA

Ball Life (Millions of Stress Cycles)	Median Rank	Rc Hardness (Avg. of 3 Readings)	Test S/N
1.4	0.02018	63.8	13*
1.4	0.04926	63.8	17*
8.0	0.07834	63.8	10*
8.2	0.10742	63.8	12*
9.2	0.13650	63.8	15*
13.8	0.16558	64.0	3
17.0	0.19466	63.8	5
18.4	0.22374	63.8	16
23.1	0.25282	63.8	11
24.1	0.28190	63.8	4
25.5	0.31098	64.0	31
39.7	0.34006	63.8	19
40.4	0.36914	64.0	18
46.2	0.39822	64.0	21
51.4	0.42730	64.0	32
53.0	0.45638	64.0	1
59.4	0.48546	63.8	39
63.0	0.51454	64.0	7
81.9	0.54362	64.0	29
94.4	0.57270	63.8	34
97.7	0.60178	64.0	40
109.2	0.63086	64.0	33
112.0	0.65994	64.0	22
126.1	0.68902	64.0	42
151.6	0.71810	63.8	9*
158.1	0.74718	63.8	23*
197.6 No Failure	0.77626	64.0	24*
197.6 No Failure	0.80534	64.0	26*
197.6 No Failure	0.83442	63.8	28*
197.6 No Failure	0.86350	64.0	35
197.6 No Failure	0.89258	64.0	37
197.6 No Failure	0.92166	64.0	38
197.6 No Failure	0.95074	64.0	41
197.6 No Failure	0.97982	64.0	43
	Requested Ball Hardness	Rc ± 1	
		Rc63 ±1	

*Balls submitted to the metallurgical laboratory for examination.

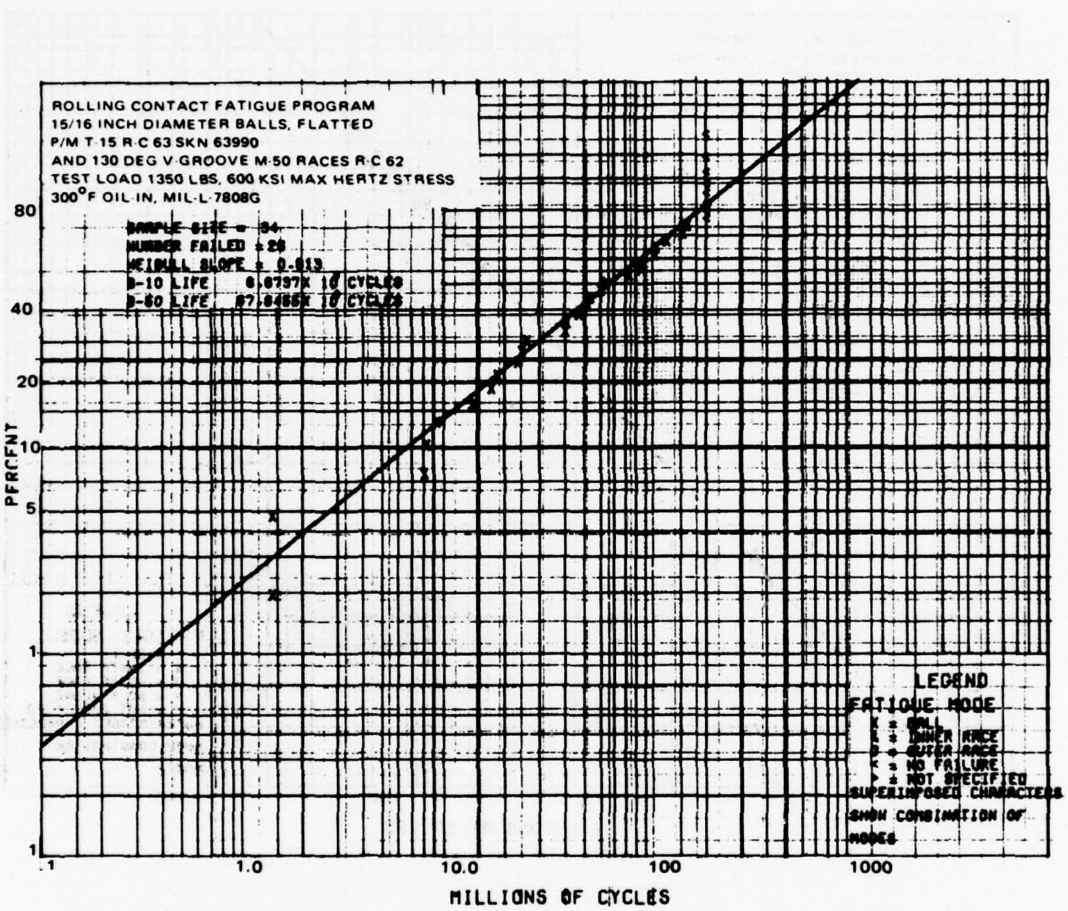


Figure 40 *<u>Weibull Curve of P/M T-15 Ball Test Results.</u> A B-10 life of 6.67 x 10^6 stress cycles was observed for this population.*

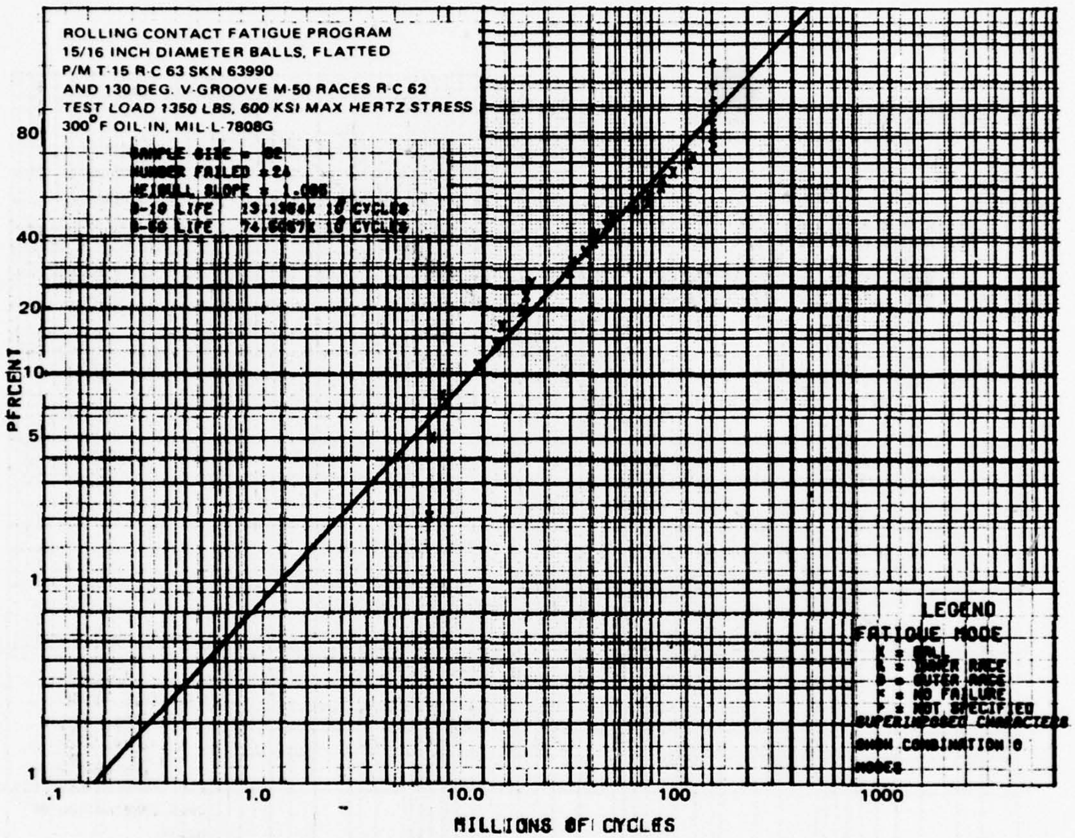


Figure 41 ___Weibull Curve of P/M T-15 Test Results After Deletion of the 2 Earliest Failures.___ *A B-10 life of 13.14 x 10^6 stress cycles was observed for this population.*

POWDER METAL PROCESSED EX00007 TEST RESULTS

Thirty acceptable fatigue test data points, the number contractually designated as that required for proper assessment of the B-10 life of a given ball lot, were obtained for the powder processed EX00007 material.

Test lives spanned a range from a low of 15.2 million stress cycles for the lowest lived ball up to the program runout limit of 197.6 million stress cycles. Six balls in this lot ran to this maximum time without failure. Table 15 lists the observed test lives, median ranks, ball hardness and test serial number of the EX00007 balls. Weibull analysis produced the results shown in Figure 42, which revealed that the B-10 life for this group was 37.6 million stress cycles. This value is approximately 2.2 times higher than the B-10 life obtained previously in tests of powder prepared M-50 balls, and 5.6 times higher than the B-10 life of the P/M T-15 balls that were also tested as part of this program.

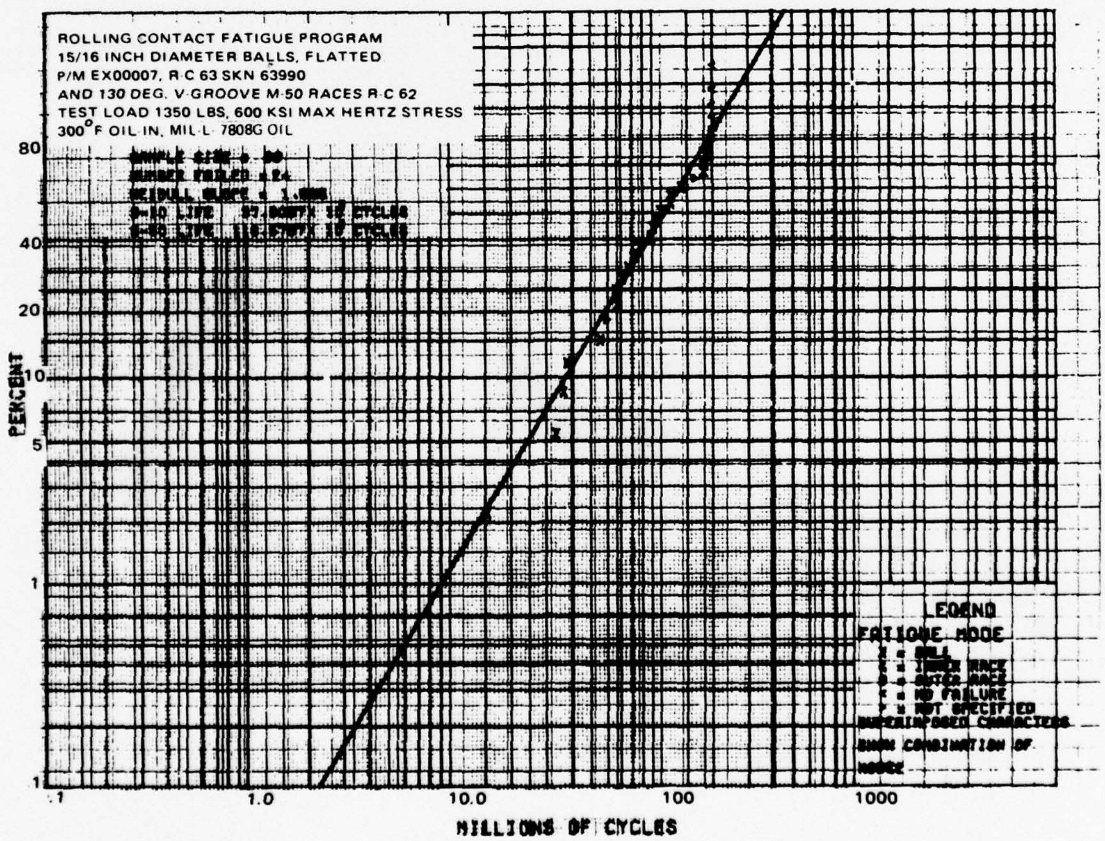


Figure 42 *Weibull Curve of EX00007 Ball Test Results. A B-10 life of 37.8 x 10^6 stress cycles was observed for this population.*

TABLE 15

POWDER METAL EX00007 BALL DATA

Ball Life (Millions of Stress Cycles)	Median Rank	Rc Hardness (Avg. of 3 Readings)	Test S/N
15.2	0.02284	62.0	35*
33.0	0.05575	62.9	65
36.1	0.08866	63.0	72
37.5	0.12156	63.0	51*
55.2	0.15447	62.5	50*
59.3	0.18738	62.5	45
66.7	0.22029	62.5	49*
66.7	0.25319	62.9	62
70.0	0.28610	63.0	20*
75.5	0.31901	63.0	61
81.1	0.35192	63.3	67
86.3	0.38482	63.3	52
98.1	0.41773	62.9	60
100.6	0.45064	63.0	43
103.3	0.48355	63.0	71
109.2	0.51645	62.9	63
122.8	0.54936	63.0	42*
122.8	0.58227	63.0	77
140.0	0.61518	62.5	86
163.8	0.64808	62.9	89
180.7	0.68099	63.0	44
181.3	0.71390	62.5	30*
187.9	0.74681	62.5	37*
189.7	0.77971	62.8	47*
197.6 No Failure	0.81262	62.5	21*
197.6 No Failure	0.84553	62.0	23*
197.6 No Failure	0.87844	62.5	59
197.6 No Failure	0.91134	63.2	70
197.6 No Failure	0.94425	62.5	88
197.6 No Failure	0.97716	62.5	90
	Requested Ball Hardness	Rc 63 ± 1	

*Balls submitted to the metallurgical laboratory for examination.

In summary of the test results, Table 16 lists the fatigue lives of the program baseline material, VIM-VAR M-50 and the three powder processed alloys. The B-10 life value of the EX00007 material exceeds that for the VIM-VAR M-50 by a factor of 1.83. Utilizing L. G. Johnson's (Ref. 1) method for assigning a confidence level to this life difference it was determined that there is 85% confidence that the observed life difference is real. Based upon this performance it is apparent that the EX00007 alloy has considerable potential for providing improved B-10 life performance in full scale bearings as compared to today's production bearings.

TABLE 16

BEARING STEEL FATIGUE LIFE RESULTS, AIR FORCE POWDER METAL PROGRAM

Alloy	No. of Tests	B-10 [$\times 10^{-6}$ Stress Cycles]	B-50 [$\times 10^{-6}$ Stress Cycles]	Weibull Slope
Program Baseline VIM-VAR M-50	15	20.56	60.78	1.74
Powder Metal M-50	30	16.99	44.05	1.98
Powder Metal T-15	34	6.67	67.65	0.81
Powder Metal EX00007	30	37.61	116.57	1.67

Test Conditions: 600 ksi max. Hertz stress
300°F oil-in temperature
Mil-L-7808G lubricant

SINGLE BALL TESTING DIFFICULTIES

In the course of testing balls in this program, an abnormal number of tests were invalidated when the balls became damaged due to heavy interference with the retainer as illustrated in Figures 43 and 44. This typically occurred at the very start of the test cycle when the rig drive was actuated. Prior single ball test program experience with this type of startup damage had shown that its cause was due either to a lack of proper attention on the part of the operator or when system lubrication was impaired, which in turn was due to an oil jet which was either plugged or misaligned. Lubrication of the ball retainer contact is not as critical during steady state operation since no contact occurs at that time as the ball assumes a stable position that is approximately .005 inch from the retainer. However, contact does occur at startup and shutdown and proper lubrication is imperative at those times. If a ball survived the initial startup, subsequent testing was normally without incident.

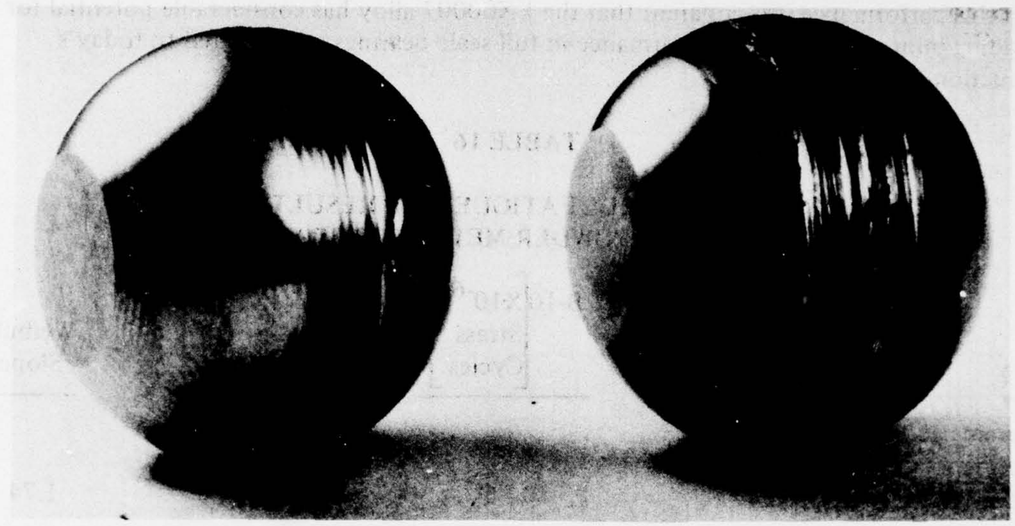


Figure 43 <u>*Typical Ball Wear Damage*</u>*. These balls typify the type of damage resulting from severe rubbing with the retainer.*

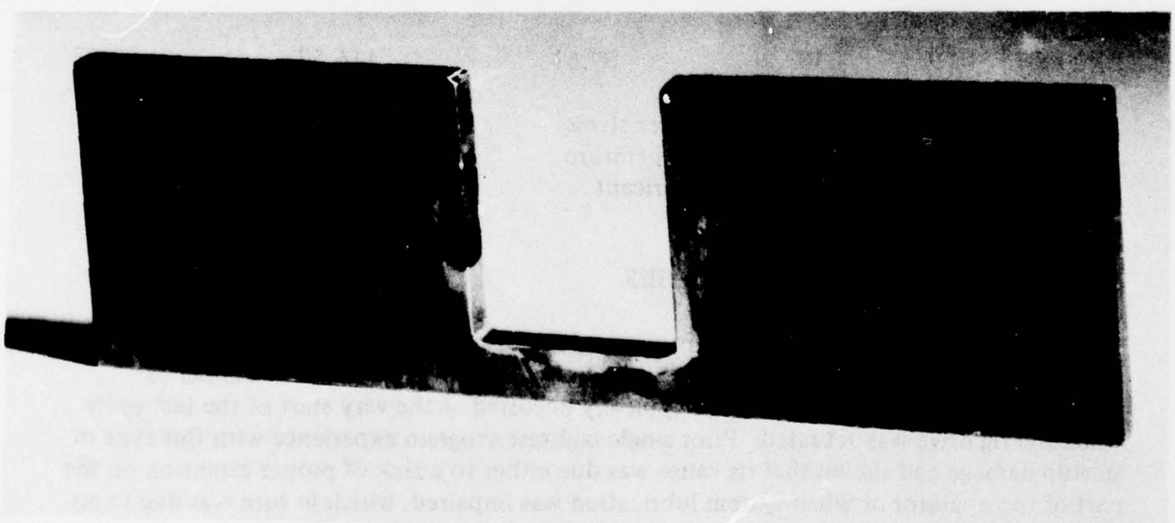
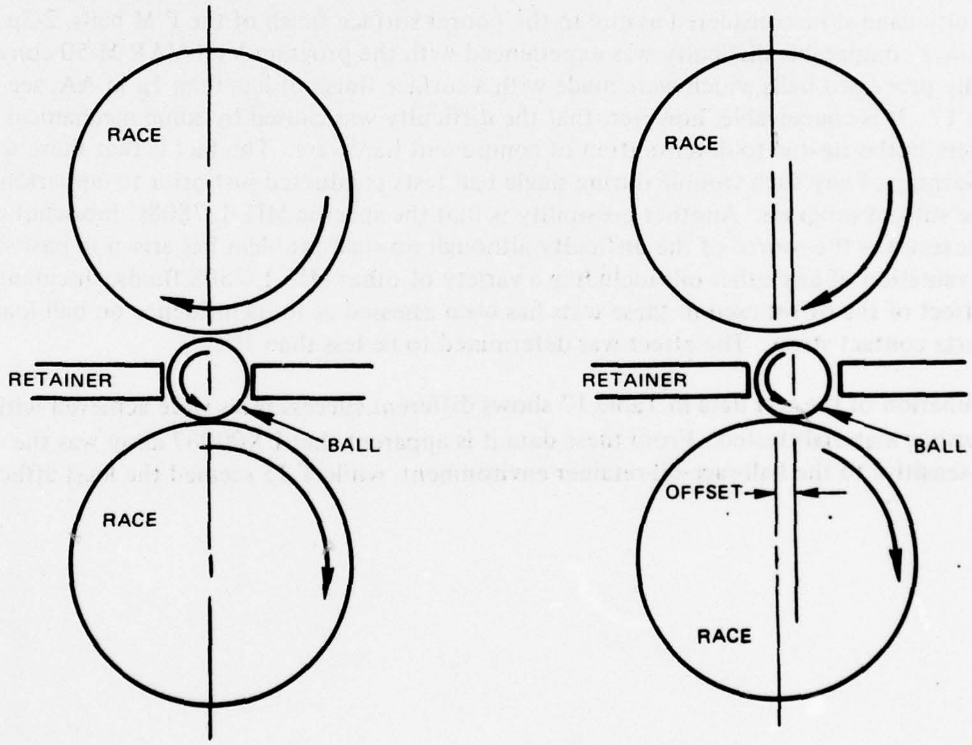


Figure 44 *Typical Cage Damage observed After Ball Rub.*

In an attempt to correct the problem of damaged balls, changes were made in both the start-up procedure and to the retainer used in the test device. However, ball damage still occurred, and subsequent inspections of the flatted balls indicated that possible imbalance due to improperly machined flats was not the cause. This investigation was integrated with actual testing with limited success in finding the cause of damaged balls. Single ball testing of the VIM-VAR M-50, powder processed M-50 and T-15 balls was conducted and completed without correcting the problem.

Ball rub of the retainer became more acute when testing of EX00007 alloy balls was undertaken. Despite taking all reasonable precautions the success rate was zero for the first 18 tests. Experimentation with ball and retainer position revealed that the success rate increased when the retainer was offset slightly to the right of the centerline of the axes of the upper and lower hubs of the test rig as shown in Figure 45.



NORMAL SET-UP

BALL & RACE CENTERS ALIGNED. RETAINER SLOT .006" GREATER THAN BALL DIAMETER. INTERNAL ARROWS INDICATE DIRECTION OF ROTATION.

MODIFIED SET-UP

BALL CENTER IS OFFSET TO THE RIGHT OF RACE CENTERS. RETAINER SLOT IS NOW .028" GREATER THAN BALL DIAMETER. INTERNAL ARROWS INDICATE DIRECTION OF ROTATION

Figure 45 Race-Ball-Retainer Alignment of Single Ball Tester

The success rate for testing the P/M EX00007 alloy balls improved considerably when the retainer was offset by .025 inch. However, as more balls were tested at this particular offset the success rate deteriorated again to an unacceptable level. Apparently some uncontrolled variables were adversely influencing the results and a level of offset was subsequently sought that would produce results less sensitive to these yet unidentified factors. Subsequent testing then revealed that an offset of .002 inch was capable of producing an acceptable success rate at least to a level that would permit completion of the planned program with the number of balls remaining.

At this juncture it is not clearly understood what caused this ball wear interaction problem with the retainer and why it was necessary to offset the ball from the rig centerlines to achieve even a 50% success rate with success being defined as operation experiencing no wear or interaction with the retainer. This type of behavior is not normal in the history of the single ball rig experience and has occurred only rarely in the past and then at a rate never exceeding 5%. This difficulty cannot be considered as due to the poorer surface finish of the P/M balls, 2-3μ in AA, since comparable difficulty was experienced with the program VIM-VAR M-50 conventionally processed balls which were made with a surface finish of less than 1μ in AA, see Table 17. It is conceivable, however, that the difficulty was caused by some mechanical problem in the rig due to deterioration of component hardware. The fact is that there was no forewarning of any such trouble during single ball tests conducted just prior to embarking on the subject program. Another possibility is that the specific MIL-L-7808G lubricant used in this test was the source of the difficulty although no such problem has arisen in past single ball evaluation of any other oils including a variety of other MIL-L-7808 fluids. Incidentally, the effect of the offset used in these tests has been assessed as to its influence on ball loading or Hertz contact stress. The effect was determined to be less than 1%.

Examination of the test data in Table 17 shows different success rates were achieved with the various materials tested. From these data it is apparent that EX00007 alloy was the most sensitive to the ball-race-oil-retainer environment, while T-15 seemed the least affected.

TABLE 17

SINGLE BALL TESTING WITH 300°F MIL-L-7808G LUBRICANT

Alloy	Tests Attempted	Tests Accepted
VIM-VAR M-50	27	15
P/M M-50	50	30
P/M T-15	41	34
P/M EX00007	87	30
Totals	205	109

The following sections present discussion of the results as indicated by analysis of the acceptable test data points.

EVALUATION OF POWDER PROCESSED BEARING ALLOYS IN THE RC TESTER

Concurrent with the P&WA single ball rolling contact fatigue tests, the AFAPL/SFL conducted fatigue tests of the powder processed alloys on an RC tester in their laboratory. The cylindrically shaped test specimens were manufactured from the same heats of powder processed alloys as those for the ball specimens. Hardness was identical to that developed in the balls evaluated in the P&WA tests. The Air Force tests developed a Hertzian contact stress level of 700 ksi maximum, compared to 600 ksi maximum in the P&WA tests. Ten tests were conducted with each material and all tests terminated because of metallic spalling. These tests revealed, see Table 18, that the powder processed EX00007 alloy provided the longest life of the powder processed materials and was superior to the life obtained for the conventionally processed vacuum-melted heats of M-50 steel. This essentially is the same result obtained from the single ball test program.

TABLE 18

USAF FATIGUE TEST LIFE RESULTS

Alloy	Rc Hardness	B-10 Life ($X10^{-6}$ Stress Cycles)	B-50 Life (X10-6 Stress Cycles)	Weibull Slope
CEVM M-50	Rc 62	2.72	5.93	2.42
VIM-VAR M-50	Rc 62	3.89	9.54	2.10
P/M M-50	Rc 62	3.87	10.26	1.93
P/M T-15	Rc 64	4.05	8.50	2.54
P/M EX00007	Rc 63	7.73	14.64	2.95

Note: Max. Hertz Stress 700 KSI MIL-L-7808 Lubricant Ten Test Points For Each Evaluation

METALLURGICAL EXAMINATION OF TESTED BALLS

Ten post-test balls from each of the powder processed alloy lots and from the VIM-VAR M-50 alloy lot were submitted to the metallurgical laboratory for examination. Five of each group were short-lived balls and the other five were long-lived balls. This choice was made in an attempt to discern if there were obvious and distinct differences between the two species.

Subsequent metallurgical examination has failed to reveal any distinctive difference between the two groups of specimens. This inability to detect differences between short-lived and long-lived specimens is not unique to the examination of powder processed alloys. This inability has also been encountered and consistently so in previous examinations of conventionally processed bearing steels. It appears that it is virtually impossible with today's methods, to differentiate between groups of short-lived and long-lived specimens since failure in both groups apparently result from the same cause.

For the metallurgical examination, a scanning electron microscope, equipped with an electron source/x-ray detection equipment (KEVEX) was employed. This equipment permitted visual study of ball surfaces and the subsequent supplemental x-ray analysis of suspect areas within the metal matrix. Specific detailed results obtained from the study of the three groups of P/M alloy balls are presented in the following sections.

Metallurgical Examination of P/M M-50 Balls

As mentioned, ten of the thirty accepted test balls were submitted to the metallurgical laboratory for examination. The specific balls submitted are indicated by asterisks in Table 13. AISI M-50 is the lowest alloyed material of the three powder processed alloys and, as such, contained the fewest carbides. Metallurgical examination revealed that this alloy appeared to be the most affected by the imposed test conditions. This is best illustrated by the degree of deformation observed along the edge of the wear track and within the wear track of ball S/N 21, a short-lived ball. Numerous pits are present and the major axes of these pits are oriented approximately 90° to the direction of ball travel as can be seen in Figure 46. The higher magnification photomicrographs, Figure 46 right and Figure 47, show in greater detail the pits or holes observed near the edge of the wear track. This region appears to be free of cracking in spite of the numerous holes.

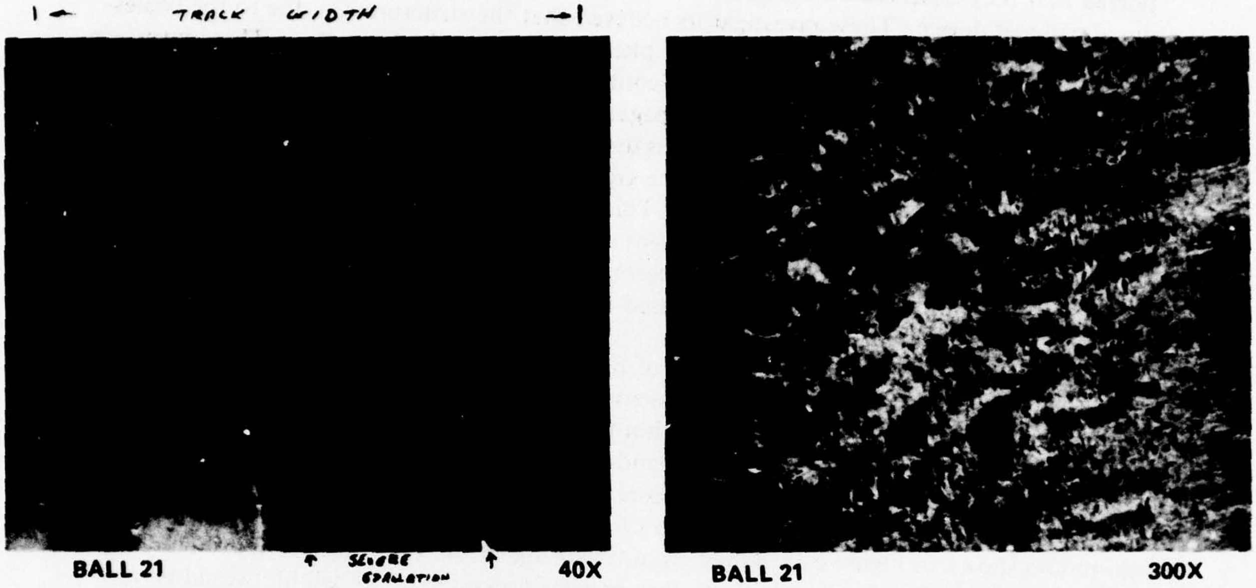


Figure 46 *P/M M-50 Wear Track Ball S/N 21. (Left) Numerous Pits are Present in Addition to the Major Spall. Lower Right. (Right) A view at higher magnification of the right edge of the wear track. This texture is promoted by plastic deformation of the alloy.*

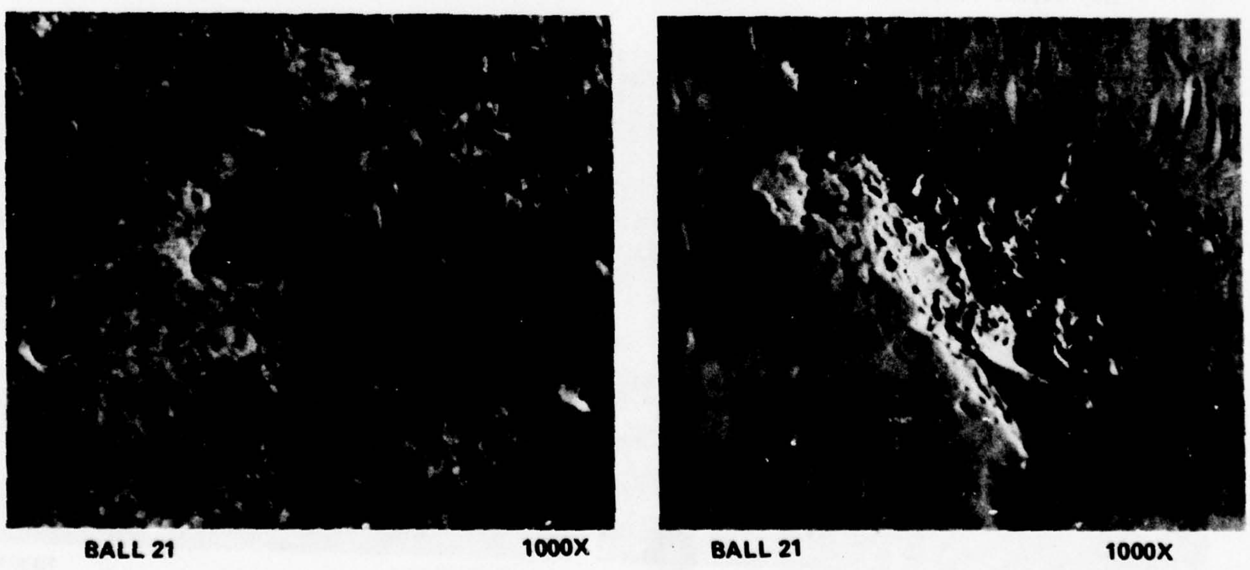
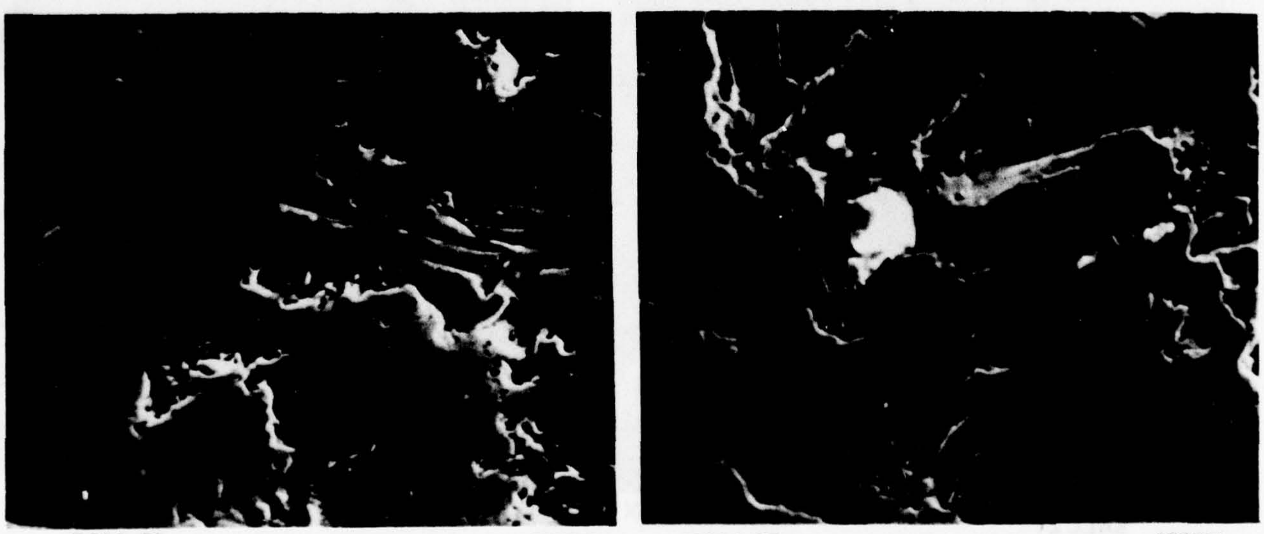


Figure 47 *P/M M-50 Wear Track Ball S/N 21. (Left) An additional Higher Magnification Study of the Deformed Region. The C-shaped markings are considered precursors of the holes. (Right) Microprobe examination of this spall and many others revealed that they developed in regions containing clusters of aluminum and silicon-rich non-metallic inclusions.*

In some similar work investigators at the Massachusetts Institute of Technology (Ref. 5) reported that they observed a similar surface texture of SAE 51100 alloy balls after testing in a 4-ball test device. These investigators believed that the structure was due to the coalescence of atomic dislocations resulting from plastic deformation of the alloy. These investigators contend that this coalescence of holes continues until the metal is so weakened that cracks appear. Once a crack occurs, it propagates through this deformed zone for a short distance before it shifts direction and moves directly into the center of the wear track. Once in the wear track the single crack fosters the growth of a myriad of sub-surface cracks which, in time, causes spalling of the ball surface. This process is a lengthy one and seemingly occurs only when other causes for spalling are absent such as surface cracks, non-metallic inclusions or excessively large carbides. The latter reason has been eliminated in this program by the refined carbides inherent in powder processed alloys.

Examination by Pratt & Whitney Aircraft of the powder metal M-50 balls has not revealed the existence of any cracking in the altered zone along the edge of the wear track. Instead all the spalls appeared to be contained within the wear track and at locations containing non-metallic inclusions. Figure 47 (right) and Figure 48, left and right, are examples of such regions. Electron microprobe analysis revealed that the regions are aluminum-rich. Figures 49, 50, 51 and 52 are X-ray traces of these spalled regions. The single peak for aluminum shown in Figure 52 resulted from traversing the particle illustrated in Figure 48 (right). These findings tend to indicate that powder processed M-50 ball life would be prolonged if these inclusions were not present. The inclusions are thought to be traces of material eroded from the ceramic vessels used in both the melting process and in the atomization of the ingot into powder. The observed inclusions were judged to be indicative of a Jernkoneret rating of ½ which is representative of the best steel quality that vacuum melting technology can provide. It appears that the presence of these non-metallic inclusions, small as they may be, are the primary cause of spalling in this powder processed M-50 alloy.



BALL 41 1000X BALL 37 1000X

Figure 48 *Other P/M M-50 Spalls. (Left) Ball S/N 41 – Microprobe analysis revealed that the many pits contained aluminum-rich particles. (Right) Ball S/N 37 – An alumina particle is visible (arrow) in the spalled region.*

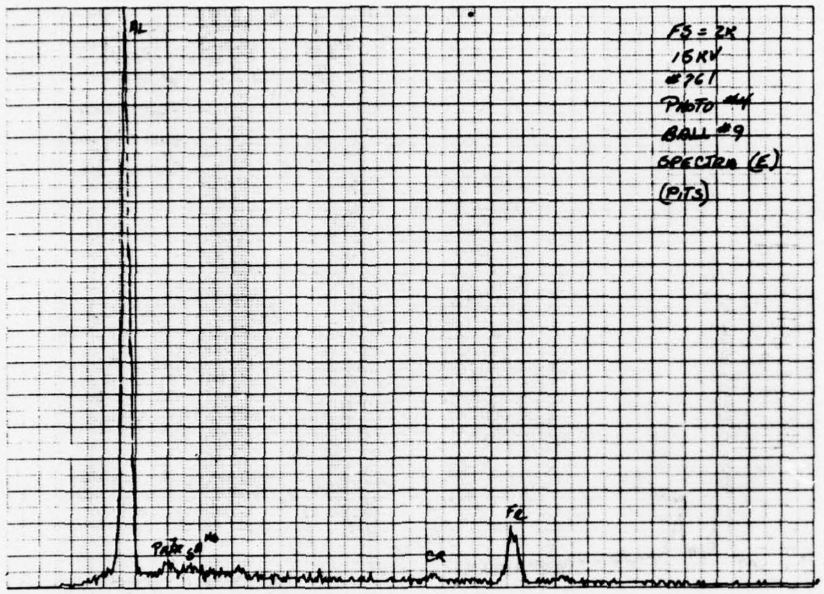


Figure 49 *Electron Microprobe Trace P/M M-50 Ball S/N 9. The trace indicates high aluminum content observed in spall region. This ball failed after 16.1 million stress cycles.*

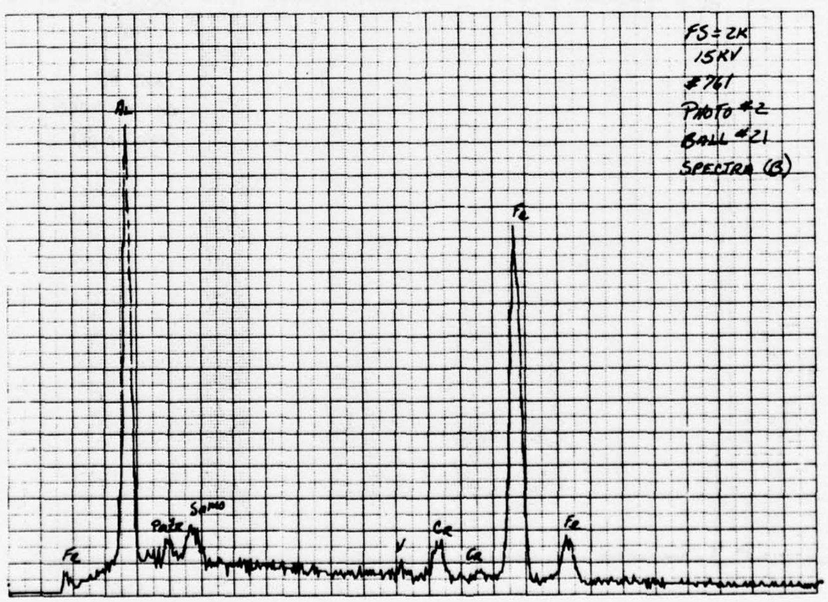


Figure 50 *Electron Microprobe Trace P/M M-50 Ball S/N 21. High aluminum content observed in X-ray trace of spall region. Ball spalled after 20.4 million stress cycles.*

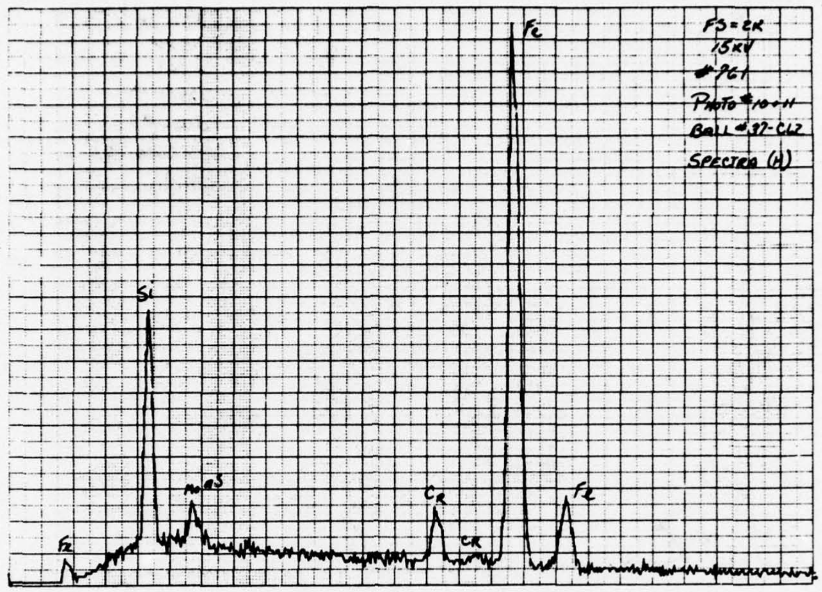


Figure 51 *Electron Microprobe Trace P/M M-50 Ball S/N 37. This trace revealed the presence of silicon. This ball spalled after 108.7 million stress cycles.*

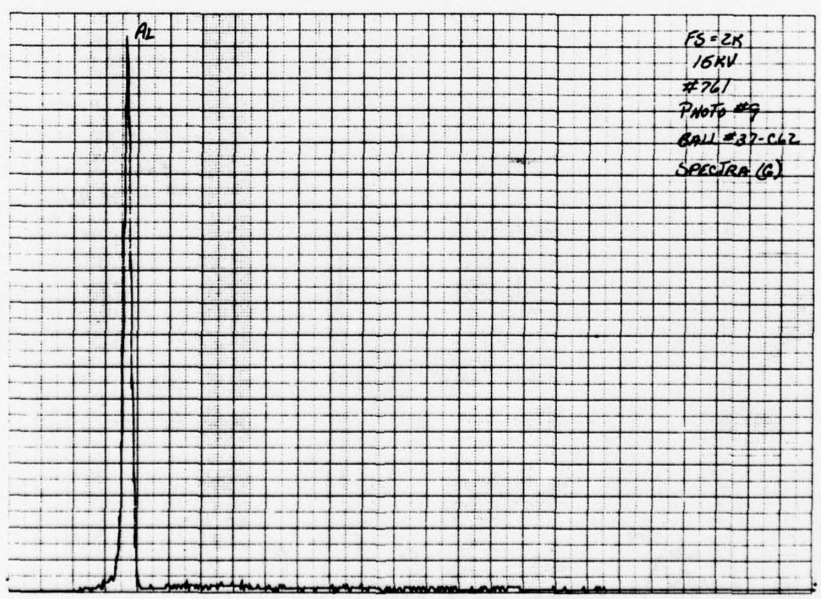
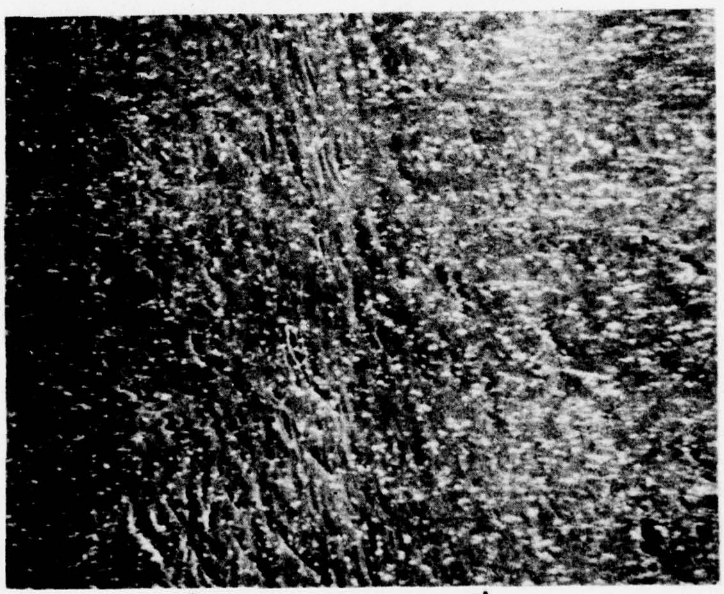


Figure 52 *Electron Microprobe Trace P/M M-50 Ball S/N 37. This trace represents the region shown in Figure 48.*

Metallurgical Examination of P/M T-15 Balls

Samples of short-lived and long-lived T-15 balls were submitted to the laboratory in order to discern if there were distinct differences between the two groups. Subsequent study did not reveal any distinct differences between the groups. The specific balls submitted to the laboratory are indicated in Table 14. In the photomicrographs of the T-15 alloy the tungsten-rich carbides stand out in contrast to both the carbides of the other alloys and the matrix metal providing the appearance of an etched surface when, in fact, the surface is not etched. This appearance results from the higher reflectance of the higher atomic weight element, tungsten, which is present in some of the carbides. Images perceived in the scanning electron microscope are a function of the atomic weights of the atoms forming the surface. The higher the atomic weight, the brighter the image.

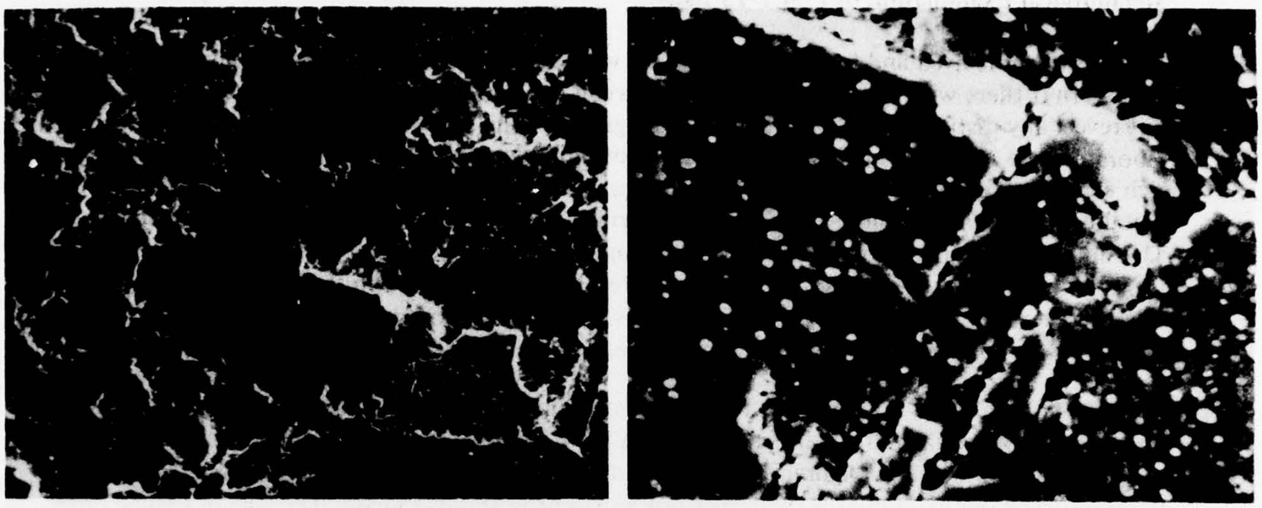
Examination of the T-15 alloy balls revealed that the material responded to the test conditions without exhibiting the deformation observed in the P/M M-50. An illustration of a typical wear track is presented in Figure 53. The region of extreme deformation along the edge of the wear track observed in M-50 balls was not apparent in this T-15 case. Damage in spalled regions are presented in Figure 54. Subsurface texture appears to be indicative of ductile fracture which may be the result of coalescence of holes below the surface. In addition, regions exhibiting numerous holes or pits were observed. Examples of typical regions are presented in Figure 55. Electron x-ray examination of these and similar regions revealed aluminum rich particles.



WEAR TRACK IMPRINTS

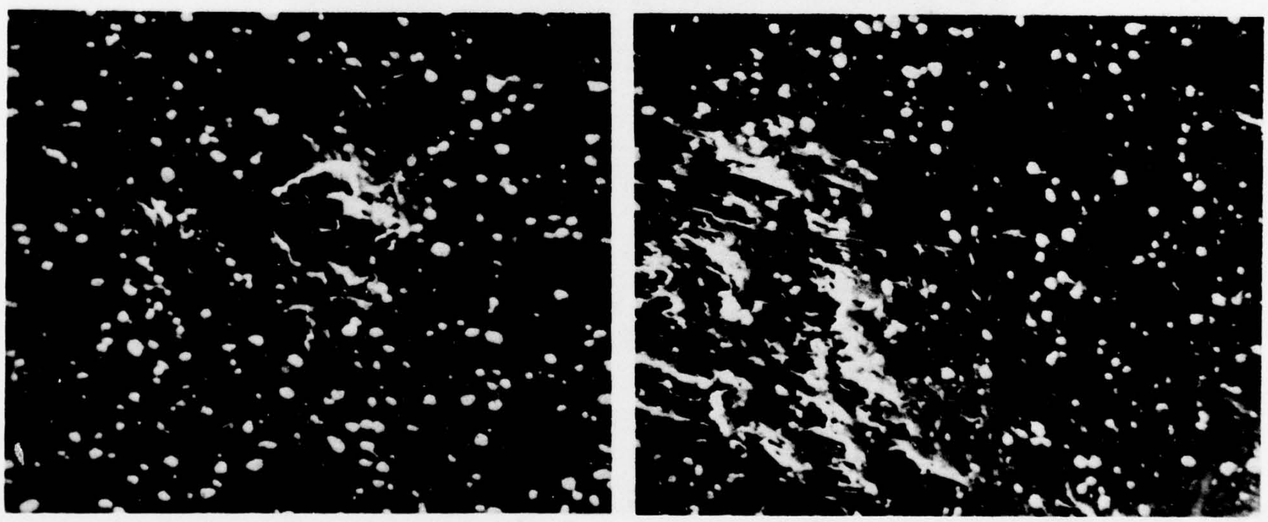
MAGNIFICATION 1000X

Figure 53 *P/M T-15 Wear Track Ball S/N 9. The wear track, oriented vertically, does not exhibit the texture observed in the P/M M-50 (See Figure 46 and 47 left). Rippling of the surface is apparent, however.*



MAGNIFICATION 300X MAGNIFICATION 1000X

Figure 54 *P/M T-15 Spall Region, Ball S/N 15.* *(Left) view of spall damage. The cavities seem to exhibit a stringy texture in contrast to the smooth surface texture. (Right) Higher magnification study of center right region. In the cavity the texture appears to exhibit a ductile texture, perhaps the result of coalescence of holes.*

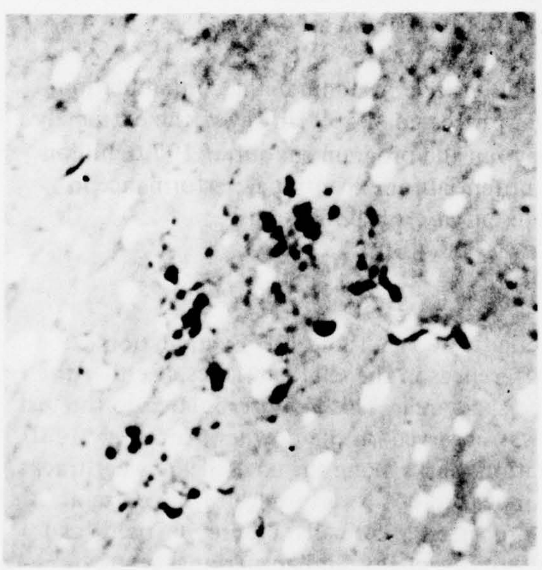


MAGNIFICATION 1000X MAGNIFICATION 1000X

Figure 55 *P/M T-15 Wear Track Regions.* *(Left) ball S/N 9. C-shaped markings are evident around an incipient spall. (Right) Ball S/N 12. Electron microprobe examination of the this spall revealed that the numerous pits contained aluminum rich particles, assumed to be alumina.*

Small amounts of aluminum are added purposely to bearing steels during the melt process to deoxidize the melt. This aluminum addition also acts to produce a fine grained ingot. This aluminum is uniformly dispersed throughout the alloy and does not appear locally in a concentrated form. Thus, any concentration of aluminum is thought to be contamination. In this case the contamination is most likely to be alumina which eroded from the ceramic crucible during the melt process. Figure 56 (right and left), presents a pitted region which revealed high aluminum concentration. It must be pointed out that the overall speckled appearance is due to the aluminum purposely added to the melt. However, the dense white regions are thought to be alumina.

The presence of similar inclusions at or near the surface of bearing components may have contributed to the early demise of the test balls. Regions were observed where a cluster of holes appeared that did not seem to be associated with non-metallic inclusions. These regions seemed to be the result of carbide fallout or defects related to poor bonding of the carbide/matrix metal interfaces. Figure 57 shows some voids in a region away from the wear track, and all appear related to carbides, and a region within the wear track where the number of holes is more numerous. It can only be assumed that the increase in number is due to the repeated stressings on the region as it moved in and out of the contact zone. This feature does not appear to be an immediate cause of metal spallation and may be analogous to the deformation illustrated in Figures 46 (right) and 47 (left).



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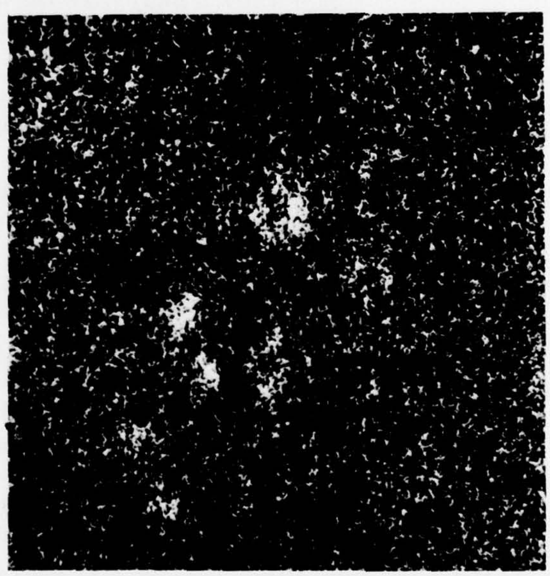


MAGNIFICATION 3000X

Figure 56 *__Aluminum Rich Region in Ball Wear Track, P/M-T-15 Ball, S/N 12.__ (Left) A pitted region in the ball wear track which provided evidence of aluminum rich particles. These regions occur in clusters within the wear track and elsewhere on the ball. (Right) An electron X-ray scan of the spall for aluminum. The dense white areas are indicative of high aluminum content.*

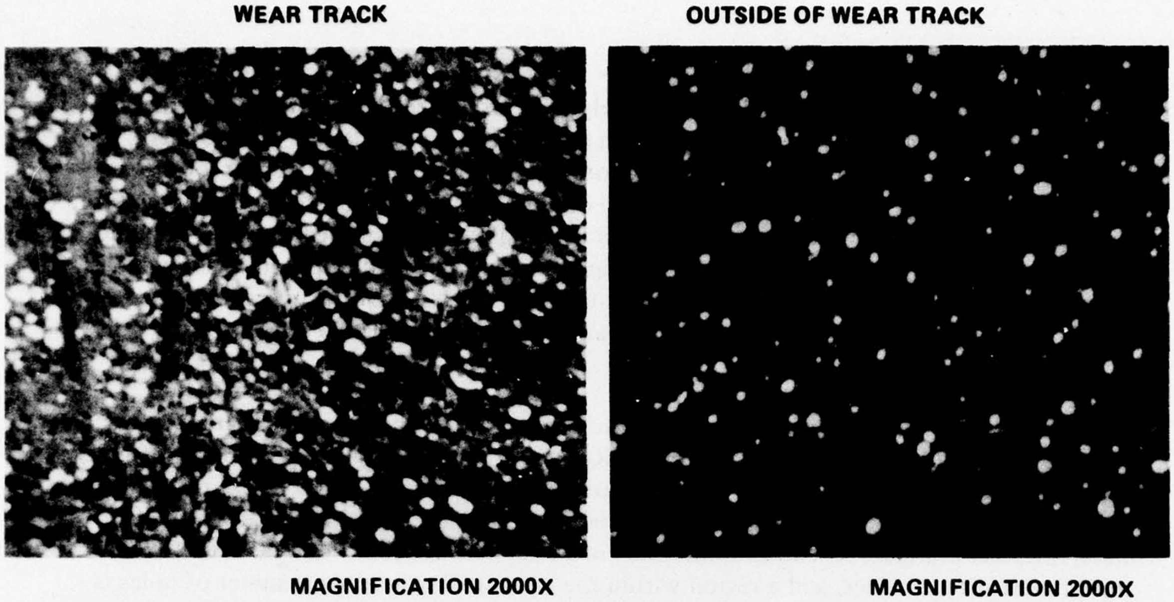
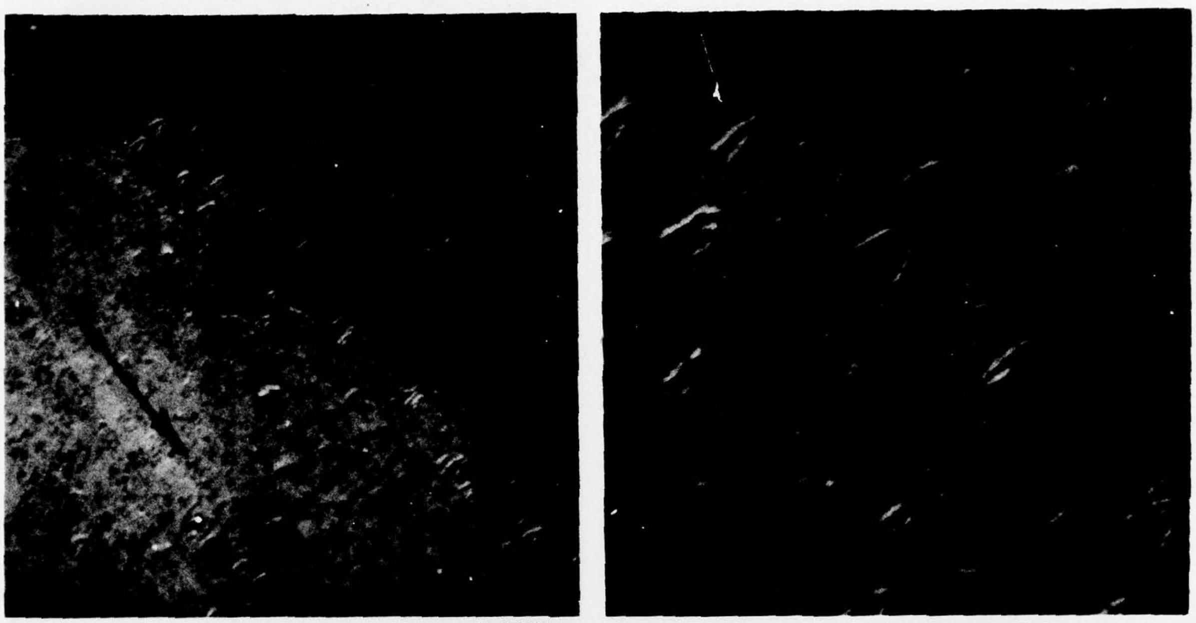


Figure 57 Holes in Surface of P/M T-15 Ball, S/N 10. (Left) Numerous holes are apparent along the edge of the wear track. They appear aligned. It is not known whether they are the result of coalescence of holes or simply due to carbide fracture and fallout. (Right) Occasional holes are present in this region which is away from the wear track. These holes seem to be associated with carbides that have fallen away from matrix metal surface.

It appears that T-15 with its many carbides is more sensitive to nonmetallic contamination since this alloy was not as long-lived as the powder processed M-50. However, the extremely long-life of some individual balls even to levels beyond the program runout of 197.6 million stress cycles does indicate that this alloy has the potential for exceptional performance in rolling contact application if inclusions are not present at critical locations.

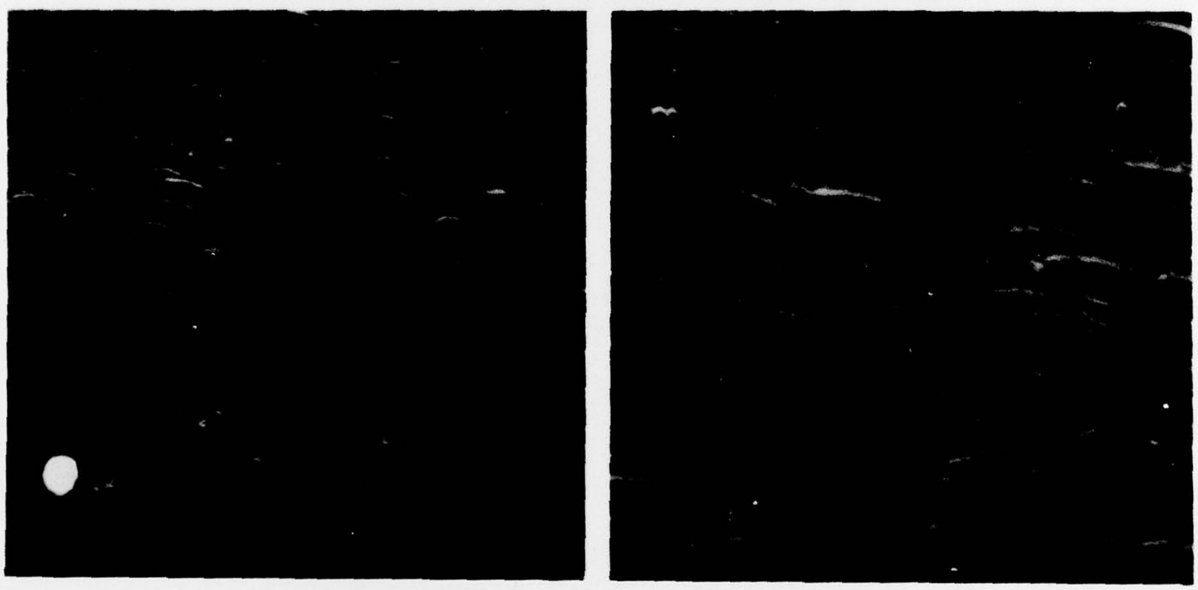
Metallurgical Examination of P/M EX00007 Balls

The specific balls submitted to the laboratory are indicated in Table 15. Examination of both the short and long lived balls revealed no differences in the characteristics of either the wear track surface or the region in and around the spall area. This alloy responded to the test conditions with less apparent deformation than was observed on the powder processed M-50 balls. Examination revealed some micro-deformation marks along the edge of the wear tracks as shown in Figures 58 and 59. These markings appear to be an early stage of the extreme deformation observed previously on the powder processed M-50 balls, Figure 46 (right) and 47 (left). By comparison, the P/M T-15 balls did not reveal any similar markings along the edge of the wear track. Subsequent electron X-ray examination of EX00007 micro-spall regions revealed aluminum rich regions thought to be alumina particles that had eroded from the melting crucible. A micro-spall region as viewed by both a scanning electron microscope and with an electron X-ray system for aluminum content are presented in Figure 60. The spectra trace for this region is presented in Figure 61. It must be pointed out that such alumina contamination is not unique to powder processed bearing steels. In the following section which is a discussion of the metallurgical findings on conventionally processed VIM-VAR M-50 steel balls, similar contamination was observed.



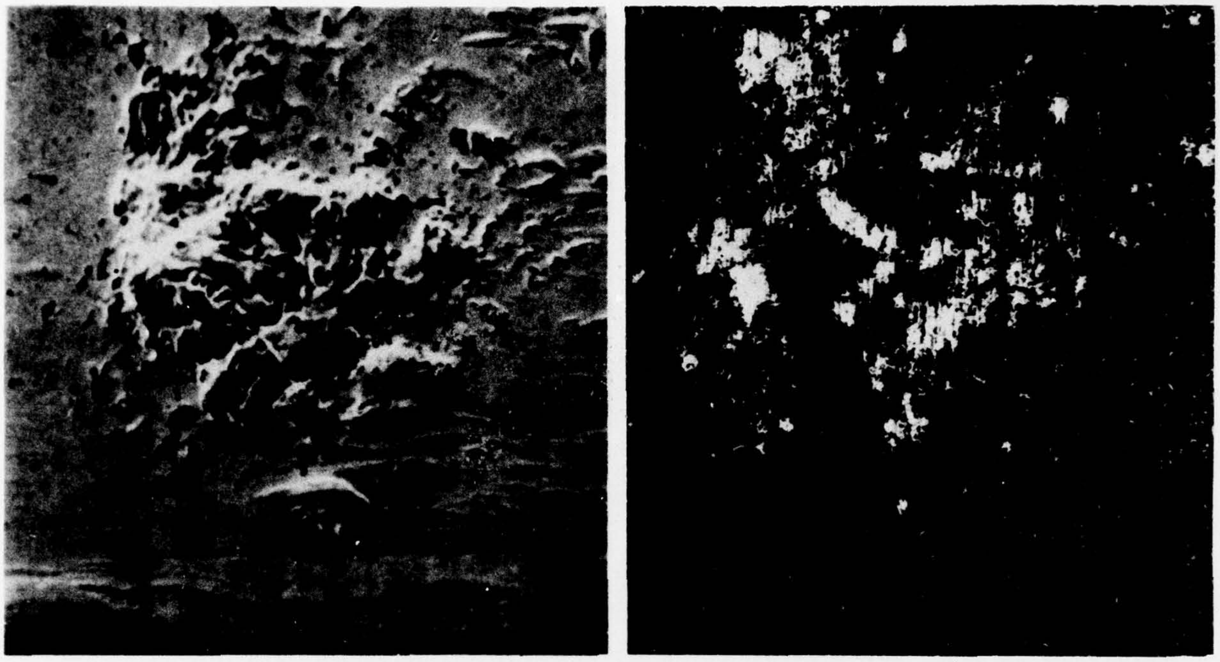
MAGNIFICATION 300X MAGNIFICATION 1000X

Figure 58 <u>EX00007 Wear Track Ball S/N 20.</u> *(Left) Edge of wear track reveals deformation markings. Arrow indicates direction of ball travel. (Right) Higher magnification photomicrograph of gothic arch shaped marks.*



MAGNIFICATION 300X MAGNIFICATION 1000X

Figure 59 <u>EX00007 Ball Wear Track Ball S/N 21.</u> *(Left) Edge of ball wear track reveals numerous deformation markings. Arrow indicates direction of ball travel. (Right) Higher magnification photomicrograph of the deformation marks revealing the cresent shape.*



MAGNIFICATION 1000X **MAGNIFICATION 1000X**

Figure 60 *EX00007 Ball Spall Ball S/N 23. (Left) A micro spall region. Arrow indicates direction of ball travel. (Right) An electron X-ray scan of the spall for aluminum. The dense white areas are indicative of high aluminum concentration.*

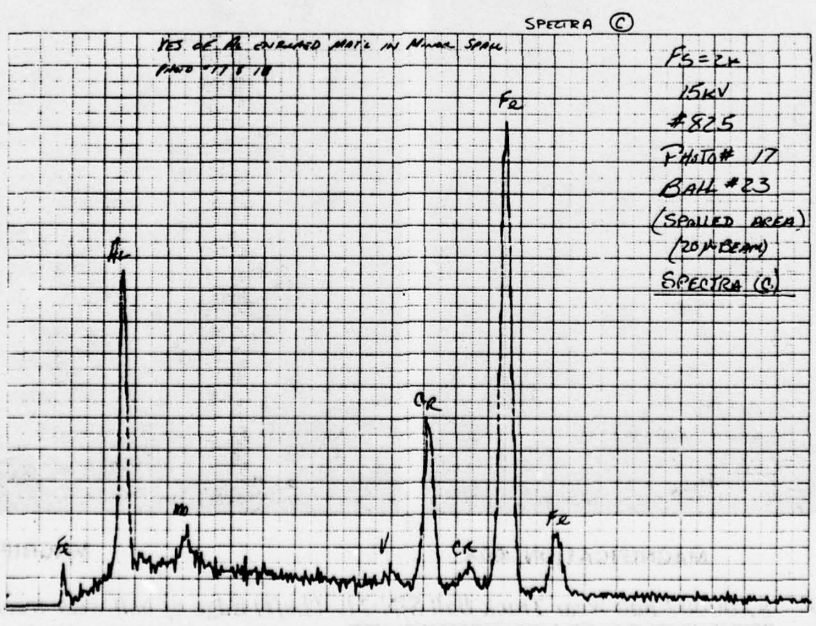
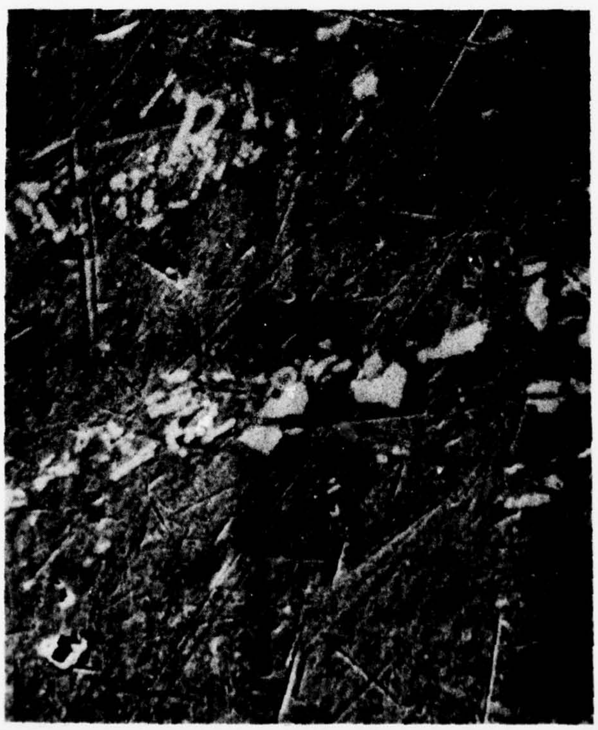


Figure 61 *Electron X-ray Spectra, EX00007 Ball S/N 23.*

Metallurgical Examination of VIM-VAR M-50 Balls

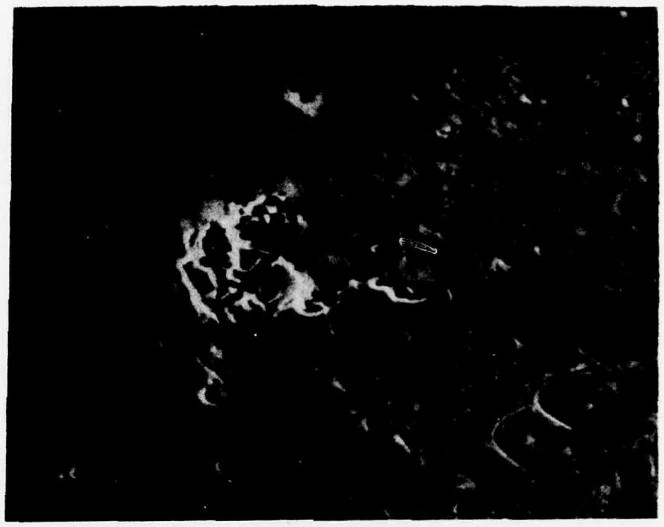
The specific VIM-VAR M-50 balls studied and reported in this section are indicated in Table 12. Again examination of both the short and long lived balls revealed no differences in the characteristics of either the wear track surface or the region in and around the spall area. This material exhibited larger carbides than observed in the powder processed alloys. They also appeared as stringers which can be seen in Figure 62. Investigators in the bearing field have observed that premature failures occur when excessively sized carbides and/or stringers of carbides exist in the bearing contact zone. An example of an incipient spall associated with a large carbide on a VIM-VAR M-50 ball surface is presented in Figure 63. The high incidence of spalls associated with large carbides has been the primary reason behind the efforts in the bearing steel preparation field to refine alloy carbides. This contract is part of that effort since powder processed metals provide the ultimate in carbide refinement and distribution.

Non-metallic inclusions, such as alumina, are also a source of spalling failure common to most bearing steels. Examination of these VIM-VAR M-50 balls revealed that non-metallic inclusions were evident in spalled regions. A typical incipient spall region observed on VIM-VAR M-50 ball S/N 9 revealed aluminum enrichment, attributed to alumina as presented in Figure 64. This region was not unique for many similar observations were made. Non-metallic contamination appeared to be as prevalent in the VIM-VAR M-50 as it was in the previously discussed powder processed bearing steels.



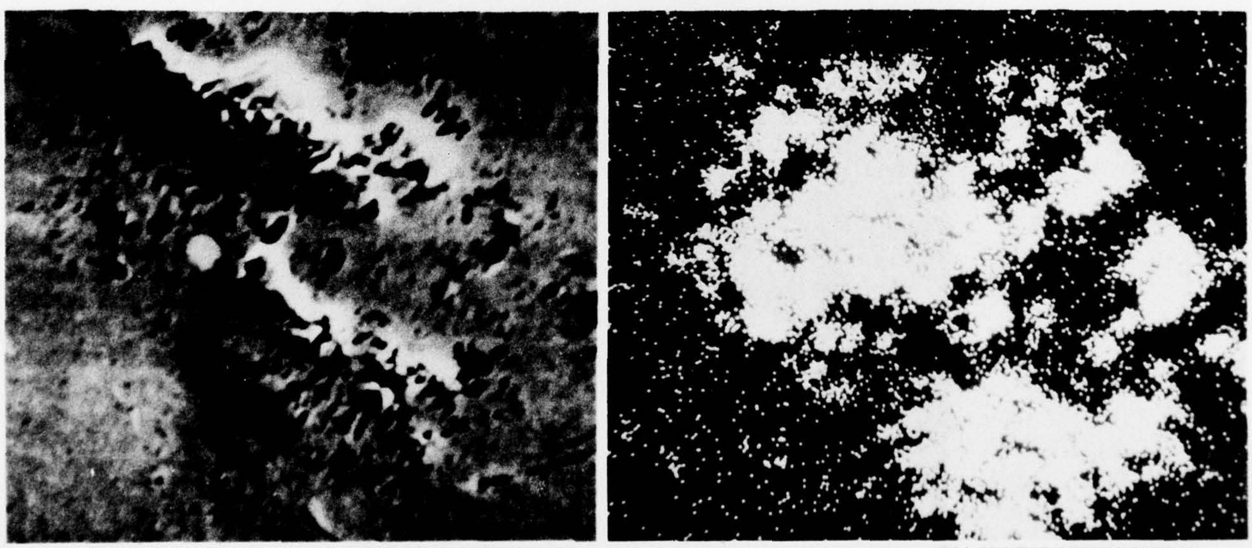
MAGNIFICATION 1000X

Figure 62 *Photomicrograph of VIM-VAR M-50 Ball, S/N 23. Carbide stringers observed outside the wear track. The larger carbides are approximately 5X the size of the carbides in the powder processed alloys. A fractured carbide is evident in the lower left corner.*



MAGNIFICATION 1000X

Figure 63 <u>*Incipient Spall on VIM-VAR M-50 Ball, S/N 23.*</u> *Spalling associated with a carbide approximately 0.001 inch long. Gothic arch markings surround the spall.*



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MAGNIFICATION 2000X

Figure 64 <u>*Incipient Spall Region on VIM-VAR M-50 Ball, S/N 9.*</u> *(Left) pitted region within ball wear track. (Right) electron X-ray scan of the pitted region indicating aluminum enrichment.*

SECTION IV

DISCUSSION OF RESULTS

The bearing ball components fabricated and tested in this program have proven to be of high quality. This is particularly notable since the alloys used in their fabrication were powder metal processed, a preparation method for which little prior experience existed as applied to bearing steels. It was anticipated at the start of this program that powder metal processing would provide a metallurgical structure consisting of a uniform dispersion of refined carbides in a matrix of similarly refined grain size. This structure was realized in the program test balls and appears to provide a microstructure that approaches the ultimate for bearing steels. An early concern of this project was that the powder metal process might introduce objectionable levels of oxygen. It is known that high oxygen content embrittles steel and renders it unfit for an application as demanding as that of rolling contact bearings. In this program the ball alloys exhibited low levels of interstitial oxygen, an indication that the steels were not penalized by any undue increase as a result of the powder metal processing.

It is quite unusual in an experimental effort of this nature to experience success with the first attempt at each and every manufacturing step. This in fact was the case for the subject program in that no particular problems were uncovered in the forging, rolling, grinding, or lapping procedures used in manufacturing of the balls. This demonstrated tractability of P/M steels as applied to bearing balls also bodes well for the use of this process in the manufacture of bearing raceways. Of course this behavior was not altogether unexpected because of the good experience with P/M processed steels as employed in the machine tool industry. The improved grindability and machinability of P/M tool steels vs conventionally processed material is well documented, e.g. reference 6. These improvements as applied to bearings would undoubtedly impact fabrication costs in a favorable way. Of course the greatest cost savings potential lies in the materials savings that would be realized through the hot isostatic pressing of powder to the near net shape of the bearing rings. Work of this nature is not within the scope of the current program but may prove attractive to pursue once the objectives of the existing contract are achieved.

The most significant achievement of the program must necessarily be that associated with the long fatigue life demonstrated for the P/M EX00007 alloy balls. The life demonstrated by these balls in the single ball fatigue test machines is the best ever observed in the long history of the use of these devices for screening candidate bearing materials and processes. The B-10 life of the P/M EX00007 alloy obtained from these tests was a factor of 1.83 times superior to that of the baseline VIM-VAR M-50 material, a material considered the industry standard and the best available in today's high quality production bearing steel market. The good quality and performance of VIM-VAR M-50 is the result of fine tuning the processing through the years. It is reasonable, then, to expect that similar efforts applied to powder metal processed EX00007, in order to fine tune its composition and processing, would also produce further improvement in its fatigue life performance.

It is interesting to further compare the results of the P/M EX00007 alloy to that of its conventionally processed counterpart and to do the same for the other two program materials, M-50 and T-15. The conventionally processed EX00007, see Figure 5 for B-10 life data, produced a B-10 life that is 1.43 times that of the comparable baseline M-50, see Figure 3. This compares to the 1.83 ratio for the P/M EX00007 tests vs the same era conventionally processed baseline VIM-VAR M-50 results, see Table 16. Neither the P/M M-50 nor the P/M T-15 exhibited any such trend. In fact, the P/M M-50 showed neither a gain nor a significant loss

and the T-15 revealed an apparent negative response in that it's B-10 life was, at best, only 0.64 times that for the conventionally processed baseline VIM-VAR M-50 results, again see Table 16. This ratio compares to a life for conventionally processed T-15 that is 1.77 times that of the baseline conventionally processed M-50 of that era, comparing data from Figure 2 with that in Figure 1A. Thus, it appears that, of the three program P/M alloys evaluated, the EX00007 material was much more responsive to powder metal processing which indicates the possibility that a further gain might be realized by means of one or a combination of the following; alloy chemistry modification, mechanical processing variation, or optimization of heat treatment and surface finish.

In spite of the superior performance of the EX00007 alloys some of the balls did fail in fatigue and certain metallurgical studies were conducted to determine the cause or causes. Examination of both spall damaged regions and incipient spall regions indicated the presence of non-metallic contamination in both the conventionally processed VIM-VAR M-50 material as well as in the P/M processed alloys. Most were identified as aluminum-rich materials, considered to be alumina. Occasionally, silicon-rich regions were also observed and these were identified as silica inclusions. The source for these non-metallics was apparently the ceramic crucible used for the initial melt of the alloy ingot. This fact has long been recognized by the raw material processors and they have worked diligently to minimize contamination from this source. The result of such efforts is demonstrated by the cleanliness provided by vacuum melted steels. In spite of the use of multiple vacuum arc remelting processing which endeavors to remove such non-metallics the presence of minute particles of these contaminants still exist below certain threshold limits. Because of this limitation all vacuum melted steels, VIM-VAR material included, exhibit some level of non-metallic contamination.

It appears that the presence of non-metallic inclusions at crucial locations within the test balls influenced ball life in this program. This is not to say that other metallurgically oriented factors did not have an influence, but the almost invariable presence of non-metallic contaminants at spall damage sites indicate more than just a coincidental relationship. It remains to be demonstrated that ball life would be improved significantly with non-metallics removed from the metal matrix. The evidence, however, does indicate strongly where future efforts should be directed. It is recognized that there are practical limits and the technology may already be there, but taking a long hard look at the problem may spark further innovative processing changes, the application of which could further improve bearing steel cleanliness and life.

SECTION V

CONCLUSIONS

Powder processed bearing steels lend themselves well to bearing ball manufacture as demonstrated by the basically trouble free experience with making balls from the three P/M program alloys; M-50, T-15 and EX00007. As was pointed out in the previous section, it is quite unusual in an experimental effort of this nature to experience success with the first attempt at each and every manufacturing step as has been the case for this powder processed ball program. This good experience bodes well for the future of powder processing technology as applied to bearing steels. When it is considered that this technology is in its infancy, it is not unreasonable to expect considerable gains in performance in the future as the process matures.

Powder metal processed balls, as fabricated for this program, developed a rougher surface finish than conventionally processed balls when lapped by the same equipment. Powder metal balls made from all three of the program alloys finished to a 2 to 3 microinch AA level versus 1 microinch AA for the conventional balls. However, this is not considered to be a problem of any basic significance since the ball roundness generated during the lapping procedure was excellent and more than satisfied the Grade 10 requirements of the program.

The results from metallurgical studies conducted as part of the elemental fatigue test portion of this program has demonstrated that powder processed steels can be prepared to cleanliness levels that equal or exceed those already established for vacuum melt steels. This fact is of considerable significance since cleanliness, or the lack of it, had previously been considered the greatest potential obstacle to the utilization of powder processing technology in the manufacture of bearing steels for aircraft gas turbine engine mainshaft applications. Demonstration of this capability may have ramifications in other applications where material cleanliness is also crucial.

This work has also shown that those nonmetallic inclusions that were still present in the powder processed steels apparently had an effect on rolling contact fatigue performance that tended to detract somewhat from the positive influence expected from the improved microstructure. Prior to testing, it had been speculated that the refined microstructure as determined from metallographic evaluation of the finished balls would result in an improvement in the B-10 life rating of all three of the program alloys. In fact, there is one school of thought that would argue that the T-15 P/M balls would have the greatest B-10 life as this alloy had the greatest number of carbides. Along with this decidedly larger number of carbides this alloy still displayed the same excellent carbide refinement and dispersion characteristics seen in the other two program alloys. The results from the single ball rig testing did not validate this argument that a larger number of carbides is best because the T-15 P/M ball group produced the shortest B-10 life of the four groups of balls tested in this program. Even though certain balls from this group exhibited the shortest lives experienced in the overall program, other T-15 P/M balls from this same group ran without failure through 40 hours, the program runout limit. From these extremes it is speculated that the difference in performance observed is a function of the presence or absence of nonmetallic inclusions in the stressed volumes of the respective balls. The fact that eight of the T-15 balls reached

the runout limit provides an indication that this alloy may have some potential for development as a P/M bearing steel. It is interesting to note, in contrast, that not one of the M-50 balls, from either the VIM-VAR lot or the powder processed lot, reached the program runout limit.

The EX00007 alloy responds favorably to powder metal processing. Examination of the EX00007 ball test data revealed that six reached the runout limit and that the B-10 life of this group was 1.83 times greater than that observed for VIM-VAR M-50 and 2.21 times better than the life value obtained in tests of the powder processed M-50. Also, earlier testing of balls made from conventionally processed EX00007 material had produced a B-10 life that was 1.43 times that of similarly processed M-50 balls. Examination of this data indicates that the powder processing technique served to improve the already good performance of the EX00007 material. Like the other two program alloys, those EX00007 P/M balls that did fail appeared to do so because of the presence of nonmetallic inclusions. At this juncture it appears to be a matter of conjecture as to why this alloy performed in a manner superior to the other two; however, based on prior bearing material development experience, it is reasonable to expect that with additional effort even further life performance gains can be realized. This would be accomplished through the optimization of certain parameters that also may prove to have a synergistic effect when combined with the good effects of powder processing. Some of the parameters of concern include initial particle powder size and subsequent sieving as it would effect both residual non-metallic contamination and the basic microstructure of the material, heat treatment to provide optimum hardness without loss of dimensional stability and surface finish processing as it would affect the terminal roughness of the ball.

SECTION VI

RECOMMENDATIONS

Powder processing of EX00007 alloy has produced life improvements over that of the conventionally processed form of this material as demonstrated by laboratory type rolling contact fatigue tests. These same tests have also shown that this alloy responds more favorably to powder processing than either M-50 or T-15. In addition, the EX00007 alloy has corrosion resistance that is undeniably better than that of M-50 steel. These factors combined present a favorable picture regarding the potential of powder processing as applied to bearing steels such as EX00007 and further investigation is warranted.

It is recommended that a sufficient quantity of powder processed EX00007 alloy be procured to allow manufacture of a quantity of main shaft gas turbine engine ball thrust bearings for subsequent endurance testing in rigs. This will provide information upon which a judgement can then be based as to the future use of this powder processed material in mainshaft production bearings for aircraft gas turbine applications.

It is also recommended that a separate effort be considered to evaluate the fatique life performance of as hot isostatically pressed (HIP) bearing balls. The purpose of this additional work would be to determine whether any fatigue life performance change would occur for bearing balls made by the more cost effective, material conserving, net shape, as-HIP process. These balls can be processed either by machining from the HIP ingot or by HIP forming directly to the ball shape. Obviously, the greatest potential cost savings would be realized from near net shape HIP forming of the bearing races as opposed to the balls, however, ball testing would be a more reasonable and logical first step for economy reasons in the exploration of this approach and is recommended for use in this proposed program.

In addition, it is also recommended that a complementary effort be considered that would focus on optimizing both powder particle size and alloy heat treatment. Exploring these variables through ball life tests conducted on elemental laboratory devices hold a strong potential for making further life gains through powder metal processing of bearing materials. Once this work had been accomplished it would then be sensible to make a group of full scale engine size bearings using the optimum processing, including as HIP form components, for subsequent rig testing to establish B-10 fatigue life capability. Such a life improvement demonstration would be a necessary step in the process of gaining acceptance for the use of advanced bearings of this type in actual production aircraft engines.

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